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IMPACT OF DRILLING AND COMPLETION
FLUIDS ON THE PRODUCTIVITY OF
HEAVY OIL RECOVERY PROCESSES

MICROMEDIA

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OBJECTIVE

The objective of this proposal is to maximize the productivity from the in situ heavy oil reserves of Western Canada. The success or failure of all in situ heavy oil recovery processes is very dependent on the quality of the wells drilled into the formation. Recent field work has shown that present well drilling and completions practices can have a very detrimental effect on well quality, and therefore can significantly influence the efficiency of the recovery process.

This project will establish the extent to which cement filtrates interact with the formation to reduce permeability and create well bore damage. This damage can severely limit oil production from all in situ recovery processes. Results obtained from the study will aid in the selection of oil well cements which minimize formation damage, reduce completion costs and ensure that optimum oil production is achieved.

Specific areas of study:-

- (i) Quantitative determination of the effect of cement filtrates on the permeability of heavy oil cores.
- (ii) Determination of the quantity and composition of precipitates formed by interactions between cement filtrates and formation water.
- (iii) Determination of the effect of ion exchange and fluid composition on the permeability of heavy oil cores.

JUSTIFICATION

The success or failure of all in situ heavy oil recovery processes is very dependent on the quality of the wells drilled into the formation to gain access to the resource. In particular, the creation of near well bore formation damage by the use of inappropriate drilling and completion fluids can have a substantial impact on well injectivity and productivity and hence on the overall viability of the recovery process. This proposal recommends that a quantitative study be made of the effect of cement filtrates on near well bore damage. Results of these tests will aid in the selection of oil well cements which will minimize formation damage, reduce completion costs and ensure that optimum oil production is achieved.

One of the most significant causes of near well bore formation damage is that produced by drilling mud filtration invasion (1). Mud filtrates, which usually have a high pH can cause (i) significant swelling of smectites or mixed layer clays, (ii) generation of fines, (iii) adsorption of organic chemicals, e.g. lignosulfonates, and (iv) blocking of flow channels by precipitates. The literature indicates that permeability decreases of an order of magnitude can occur in the presence of alkaline fluids. Previous work carried by the Gulf Canada R&D Department shows that use of fresh surface waters and fluids with high pH values is very damaging to heavy oil cores (2).

Spacers or cement preflushes, containing mud thinners, dispersants and sometimes gelling agents, are another source of formation damage. Some spacers form precipitates when mixed with formation waters, cement filtrates and drilling muds. These precipitates then become a potential source of formation damage by plugging flow channels.

After wells are drilled they are normally completed by casing and cementing. The cementing step is another source of near well bore damage due to cement filtrate invasion of the formation. Excess fluid contained in cement is lost to the formation as the cement is cured. Supersaturated and unstable solutions are formed containing high concentrations of calcium and alkali cations, sulfate and hydroxide (3,4). This high pH filtrate, which can remain in contact with the formation for long periods of time, can cause interaction with the clay minerals, formation water and drilling mud filtrate. In addition, the reaction of cement filtrates with carbon dioxide in the formation is almost instantaneous causing calcium carbonate precipitation.

Formation damage in the vicinity of the well bore is a major cause of (i) reduced oil production rates (5,6), (ii) poor injectivity, e.g. steam and air, (iii) poor vertical conformance at both injection and production wells, (iv) premature well abandonment, (v) need for increased frequency of well workovers, (vi) lost revenues, and (vii) decreased effectiveness of thermal recovery processes.

In the oil industry, drilling and completion fluids have traditionally been selected on the basis of their (i) physical properties, (ii) material costs, and (iii) ease of use (3,7). Little or no consideration is given to the impact of the fluids on the formation and therefore the primary objective of drilling the well in the first place, i.e. to obtain access to the resource, can frequently be negated. The results of the proposed tests should lead to the selection of fluids which both meet the above three criteria and also minimize formation damage.

SUMMARY

A laboratory study of the impact of cement filtrates on the near well bore permeability of unconsolidated heavy oil reservoirs has been conducted. Two thermal oil field cement filtrates and preserved cores from Pelican Lake and West Edam were used for the study.

The filtrates from Ciment Fondu and API Class G/silica flour cement reduced the permeability of all cores except one. Decreases in permeability of up to 78% occurred. In the field the distance this damage extends beyond the perforations will be dependent upon the cement filtrate losses and the porosity of the reservoir.

The cement filtrates were incompatible with Pelican Lake and West Edam formation waters and formed significant quantities of precipitates upon mixing. API Class G/silica flour filtrate precipitated calcium and magnesium. However, Ciment Fondu filtrate precipitated aluminium (from the cement filtrate) in addition to calcium and magnesium and produced a much greater amount of precipitate. The reservoir damage will be dependent upon the amount of precipitate and its distance from the perforations.

Various components of the cement filtrates interacted with the cores. Reductions in hydroxide, total alkalinity and potassium occurred. The hydroxide reaction with clays usually results in clay expansion and a decrease in permeability whereas the potassium ion exchange with the clay usually results in clay stabilization.

It should be possible to formulate cements which produce less damaging filtrates.

CONCLUSIONS AND RECOMMENDATIONS

The effect of two thermal cement filtrates on the permeability of heavy oil cores from Pelican Lake and West Edam has been studied under laboratory conditions. The following main conclusions and recommendations have been reached on the basis of the experimental results:

- ° The filtrates from Ciment Fondu and API Class G/silica flour cements reduced the permeability of all heavy oil cores except one. Decreases in permeability of up to 78% occurred.
- ° The cement filtrates were incompatible with Pelican Lake and West Edam formation waters and formed significant quantities of precipitates upon mixing.
- ° The cement filtrates were very sensitive to carbon dioxide. The presence of carbon dioxide caused immediate precipitate formation in the filtrate. Cement filtrates are likely to cause more well bore damage in reservoirs with significant carbon dioxide concentrations.
- ° The chemical compositions of the Ciment Fondu and API Class G/silica flour cement filtrates were very different. The Ciment Fondu filtrate was very fresh whereas the API Class G/silica flour filtrate contained almost an order of magnitude higher dissolved solids primarily as potassium sulfate. The total alkalinity of Ciment Fondu filtrate was less than half that of API Class G/silica flour. Low salinity and high pH fluids are generally damaging to cores.
- ° The total alkalinity and hydroxide concentrations of both cement filtrates were reduced by reaction with the cores.
- ° The potassium concentration in the API Class G/silica flour cement filtrate was reduced probably by ion exchange with the cores. This reaction is probably beneficial since potassium is a well known clay stabilizer.

- ° The physical properties of clay minerals are dependent upon the exchangeable cations carried by the clay and the composition of the fluid in contact with the clay. Thus, the salinity and composition of the waters used to mix the cement will be a factor in limiting well bore damage. The addition of a small amount of a potassium salt to the water used for mixing Ciment Fondu should be beneficial from a reservoir damage viewpoint but cement properties such as thickening times would have to be checked.
- ° The cement filtrates were not compatible with waters containing magnesium salts (e.g. as at West Edam). The presence of magnesium caused the hydroxide to precipitate.
- ° Mixing of either Ciment Fondu or API Class G/silica flour filtrates with reservoir waters caused calcium precipitation.
- ° The aluminium in the Ciment Fondu filtrate precipitated upon mixing with either Pelican Lake or West Edam formation waters.
- ° Where cement filtrates cause significant permeability reduction by (i) interaction with core minerals, (ii) by precipitate formation upon mixing with incompatible reservoir waters or (iii) by reaction with carbon dioxide, fluid loss additives should be added to minimize reservoir damage.

1. BACKGROUND

The in situ oil sands of Canada are contained in relatively shallow geological formations composed largely of immature quartz sands with feldspars, micas, chert, marcasite and some trace minerals. Clay minerals occur interbedded in the sand as pore fillers and grain coatings. The following clays are present: kaolinite, illite, chlorite, montmorillonite and mixed layer clays (8).

Montmorillonite, degraded illite, degraded chlorite and some mixed layer clays are particularly water sensitive. The physical properties of these clays are largely dependent upon the exchangeable cations carried by the clay and the composition of the fluid in contact with the clay (9). In heavy oil reservoirs these clays are in a relatively collapsed state, but can swell extensively if contacted by fluids of lower salinity, different composition and higher pH than the reservoir water. Incompatible fluids can cause expansion of individual flakes, splitting of particles and deflocculation of the clays from quartz grains (10,11). This results in the destabilization of the near well bore reservoir structure, and the creation and migration of fine particles with subsequent bridging and plugging or pore throats. This can result in a significant and irreversible reduction in formation permeability (12).

Clay minerals are generally more compatible with low rather than high pH fluids (13). Not only are expandable clay minerals of concern, but problems of increased cleavage, or slaking reactions, of non-swelling clays occur as the water becomes more alkaline. Thus, even in formations that contain only illite and kaolinite, permeability reduction can occur with high pH fluids (14). Previous Gulf Canada R&D studies have shown that contact of heavy oil cores with low salinity or high pH fluids can result in a significant and largely irreversible reduction in permeability (2).

Bentonite drilling muds used for drilling and heavy oil reservoirs are usually prepared with low salinity surface waters. Most mud filtrates have pH values in the 8.0 - 13.0 range due to the use of additives such as sodium carbonate, sodium hydroxide and calcium hydroxide (7). Filtrates produced from well casing cements typically have pH values of 11.0 - 13.0. Unpublished Gulf Canada R&D studies show that these fluids can cause permeability decreases of an order of magnitude and that the damage due to the mud filtrate is largely irreversible.

Another source of near well bore damage is the formation of precipitates. Analyses of formation waters from Alberta and Saskatchewan indicate that many of them contain high concentrations of calcium and magnesium and would be incompatible with drilling and completion fluids containing hydroxides and carbonates (2). In addition, many drilling and completion fluids are themselves incompatible and form precipitates when mixed. These insoluble compounds can reduce permeability, or even plug wells, and can produce more stable water/oil emulsions.

The effect of near well bore damage on productivity depends upon the loss in permeability and the radius of the area affected (15). The theoretical productivity impairment from near well bore damage can be calculated based on a simplified radial flow system, described by the following equation:-

$$\frac{J_s}{J_0} = \frac{F_k \log r_e/r_w}{\log r_s/r_w + F_k \log r_e/r_s}$$

where:

J_s/J_0 = productivity after damage/undamaged productivity,

r_w = well bore radius, r_s = radius of damage zone,

r_e = drainage radius, k_s = permeability of damage zone

k_0 = permeability of undamaged reservoir,

$F_k = k_s/k_0$

For example, if the permeability of the near well bore area is reduced by an order of magnitude and if the damage extends 12 inches from the well bore, then the well will have a 62% loss in productivity (15).

The oil industry has generally only considered the physical properties and costs of drilling and completion fluids. Data available on the chemistry of these fluids and their interactions and their impact on well bore permeability are very inadequate. There is, therefore, a need to better define and quantify these effects and this proposed study seeks to address this need. It is believed that the results of this study will aid in the selection of drilling and completion fluids which minimize formation damage, reduce completion and workover costs and ensure that optimum oil production is achieved from thermal recovery processes.

2. EQUIPMENT SET UP AND TESTING

2.1 Core Displacement Equipment

Hassler core flooding equipment was set-up and tested under reservoir temperature and pressure conditions. All metallic components, e.g. diffusers, tubing, etc. were fabricated from corrosion resistant Hastelloy C.

Pressure transducers were used for monitoring differential pressures across the core samples. Pressure taps were installed at the face of each core. Fluids were injected into the core plugs using precision, high pressure Milton Roy pumps.

2.2 Filtration Apparatus

A high pressure filtration apparatus for preparation of cement filtrates was constructed. Nitrogen was used as the pressurizing gas and as the inert atmosphere required to minimize decomposition of the filtrates.

Experience has shown that standard filtration equipment is completely inadequate for preparing these types of filtrates, where fine filters (0.45 μ) are required, and where the integrity of unstable fluids has to be maintained. Hence, an effective system for preparing the various completion fluid filtrates under controlled conditions is an essential experimental requirement if reliable data are to be obtained in the subsequent tasks.

3. CORE PREPARATION AND CONDITIONING

3.1 Core Preservation and Cutting

Heavy oil cores from Gulf Canada's Pelican Lake heavy oil property in Alberta and West Edam in Saskatchewan were used in this study.

The original Pelican Lake and West Edam whole cores were carefully preserved in dry ice during transportation and stored in a freezer after being received at Gulf R&D. Handling of sections of the core, during plug preparation, was minimized and cooling with dry ice was always used during necessary handling.

The following procedure was consistently used in each of the displacement experiments:-

- ° The core plug was mounted in a teflon sleeve into a Hassler-type core holder. All core plugs used in this set of experiments were 2.5 cm in diameter, and varied in length between 3.6 and 6.9 cm (Table 6).
- ° The mounted plug was left to thaw for at least 24 hours under a confining pressure of 1000 - 1100 psig. The confining pressure was maintained throughout each experiment, until all measurements were completed and samples were collected.

3.2 Core conditioning

To standardize the initial conditions and to be able to make meaningful comparison between different runs, each core plug was flushed with toluene followed by pentane until it was completely cleaned of the original reservoir fluids. The core plug was then dried with nitrogen.

The dry core plugs were saturated with the appropriate filtered, de-gassed synthetic formation water or produced formation water. The fluid was allowed to flow through for several hours. After ensuring complete saturation, as indicated by the absence of air bubbles and the constancy of pressure drop at a specific flow rate, the pore volume was determined through a mass balance on brine injected and produced.

Each core was conditioned with either synthetic formation water or produced formation water until equilibrium was reached between the core and the water. This step established the base line permeability of each core sample.

Accurate flow measurements were also taken. At steady-state conditions, a brine sample was collected, over a recorded period of time, and weighed. The pressure drop across the core plug was, simultaneously, measured using a transducer-recorder arrangement. Knowing the viscosity of brine and dimensions of the core plug, the absolute permeability was calculated according to Darcy's law. Flow measurements were repeated and the average permeability was calculated. Care was taken to consider only permeability values within Darcy's flow regime, i.e. linear pressure drop-flow rate relationship.

Fresh core samples were prepared for each combination of fluids, to be studied.

4. PREPARATION OF FLUIDS AND CEMENT FILTRATES

4.1 Produced Formation Waters

Pelican Lake water was obtained from the well head at 12-16-81-22 W4M. This water was much less saline than that typical of the Pelican Lake area, Table 1. West Edam water was obtained from the well head at 1C-31-48-2 W3M, Table 1.

These waters were filtered through a 0.45 u Millipore filter, degassed and stored under vacuum.

4.2 Synthetic Formation Waters

The compositions of both Pelican Lake and West Edam waters were modified to prevent calcium carbonate and magnesium hydroxide precipitation upon contact with cement filtrates. The Pelican Lake synthetic water was formulated to contain 1900 mg Na/L and 110 mg K/L as the chloride. These sodium and potassium concentrations are typical of the Pelican Lake area. The West Edam synthetic water was formulated to contain 16 000 mg Na/L and 250 mg K/L as the chloride. The analyses are shown in Table 2.

These waters were filtered through a 0.45 millipore, degassed and stored under vacuum.

4.3 Cement Filtrates

Two thermal oil field cement formulations shown in Table 4 were used. A 1000 g of powder (i.e. 750 g API Class G + 250 g SiO₂ or 1000 g Ciment Fondu) were mixed with 466 mL of lake water (Table 3) for 10 minutes in an enclosed plastic container. The blend was filtered using fluted paper in a nitrogen atmosphere in a glove box. The filtrate was collected and filtered through a 0.45 millipore filter using nitrogen pressure. This entire experiment was performed in a glove box with a nitrogen atmosphere. The filtrate was stored in plastic containers under nitrogen to prevent decomposition due to the reaction with atmospheric carbon dioxide. This experiment was repeated until sufficient volume of filtrate was obtained for each core flood experiment or fluid compatibility test. The filtrate was always prepared immediately before use. The analyses of the API Class G + Silica Flour and Ciment Fondu filtrates are shown in Table 9.

5. FLUIDS CHARACTERIZATION

5.1 Chemical Composition

Produced formation waters, synthetic formation waters, cement effluents, core effluents and precipitates from fluid compatibility tests were analyzed. The methods were as follows:-

Potentiometric titration	-	hydroxide, carbonate and bicarbonate
Ion chromatography	-	chloride and sulfate
Plasma emission spectrometry	-	metals

An anion/cation balance was done on all aqueous samples.

5.2 Viscosity

Viscosity measurements were made on all fluids used for permeability determinations (Table 7).

6. CORE DISPLACEMENT STUDIES

6.1 Core Permeability Studies with Synthetic Formation Water

The effects of the cement filtrates on the permeability of heavy oil cores were determined by core displacement experiments. Core samples from Pelican Lake and West Edam were used. The first set of runs used core samples conditioned with synthetic formation water. The use of synthetic water avoided the creation of precipitates within the core when the cement filtrates were injected. Any permeability changes that took place in the presence of the cement filtrate were due only to core/filtrate interactions and not due to plugging with precipitates caused by the mixing of incompatible fluids.

This set of runs consisted of the following:-

- (i) Pelican Lake core with API Class G/silica flour filtrate
- (ii) Pelican Lake core with Ciment Fondu filtrate
- (iii) West Edam core with API Class G/silica flour filtrate
- (iv) West Edam core with Ciment Fondu filtrate

A typical fluid sequence through each core sample was as follows:-

- (i) Synthetic Formation Water to Establish the Baseline Permeability: Synthetic formation water was pumped overnight or longer until the pressure drop across the core was constant. The Darcy Regime was determined.
- (ii) Cement Filtrate: Five pore volumes were pumped followed by a twenty hour soak period (to represent fluid loss as well as shut in period in the field). Then an additional five pore volumes were pumped. Core effluents were collected.
- (iii) Synthetic Formation Water to Determine if any Damage Created in (ii) is Reversed: Synthetic formation was pumped overnight. The following day a Darcy Regime was run.

During steps (ii) and (iii) the core effluents were collected in pore volume increments for subsequent analysis. These analyses provided some insight into any ion-exchange reactions that occurred in the presence of the cement filtrate.

6.2 Core Permeability Studies with Produced Formation Water

A further series of four additional core tests were made. In this set of runs the cores were conditioned with actual formation water. Under these conditions any permeability changes that occurred when the cement filtrate was introduced were due to the combined effects of core/filtrate interactions and precipitate formation. The four additional cores had the same combinations described above. (Table 5).

6.3 Core Displacement Results

- **Pelican Lake Synthetic Formation Water**

Figure 1A shows the effect of API Class G cement filtrate on the permeability of Pelican Lake core that had been equilibrated with synthetic formation water. As can be seen the permeability was reduced by approximately 50% in the presence of the filtrate. However, most of the original permeability was restored when the core was again flushed with formation water. Figure 1B shows that the pressure drop/flow rate relationship remained essentially unchanged before and after treatment with the cement filtrate.

During the period the cement filtrate was flowing through the core, pore volume increments were collected from the core outlet. Samples of effluent were also collected during the period that the core's permeability was being restored by the formation water. These samples were analyzed to determine the nature of the processes operating during the change in permeability and are discussed in Section 7.

Figures 2A and 2B show the permeability changes and flow rate relationship for Pelican Lake core treated with Ciment Fondu filtrate. As with the Class G cement filtrate the permeability of the core was significantly reduced in the presence of the Ciment Fondu filtrate. However, reflooding the core with formation water did not recover as much of the permeability. The permeability was reduced by 18.2% (Table 8).

- **Pelican Lake Produced Formation Water**

Pelican Lake cores 6 and 7 were conditioned with actual formation water. Under these conditions any permeability changes that occurred when the cement filtrate was introduced were due to the combined effects of core/filtrate interactions and precipitate formation (Table 8 and Figures 3 and 4).

Ciment Fondu filtrate in the presence of produced formation water did not damage core #6 (Figures 3A and 3B). This result was unexpected particularly when these fluids produce a significant quantity of precipitates when mixed (Section 8.2). It is not known if this particular produced water caused damage itself. This produced water was contaminated with fresh water from another zone and is much lower in salinity than the pure formation water.

Figures 4A and 4B show the effect of API Class G cement on the permeability of Pelican Lake core 7 that had been equilibrated with produced water. The permeability was reduced by approximately 55% in the presence of the cement filtrate. However, further injection of produced water caused additional core damage which resulted in a 78.2% loss in permeability (Table 8).

- **Edam Synthetic Formation Water**

Figures 5A and 5B show the effect of API Class G + silica filtrate on the permeability of West Edam core 2. The cement filtrate reduced the permeability by 56% but part of the permeability was restored when the core was flushed with synthetic water giving a final loss in permeability of 37.4% (Table 8).

Ciment Fondu filtrate reduced the permeability of West Edam core 3 by only 7% but a further reduction occurred upon injection of formation water for an overall loss of 16.2% (Table 8 and Figures 6A and 6B).

- **West Edam Produced Formation Water**

Both API Class G + silica and Ciment Fondu filtrates caused severe core damage in the presence of produced West Edam water, Table 8 and Figures 7A, 7B, 8A and 8B. The permeabilities of cores 4 and 5 were the highest at 1354 and 1272 mD but were reduced by 34.5 and 48.4% (Table 8). Generally high permeability cores are less susceptible to damage than low permeability cores.

7. CORE EFFLUENT COMPOSITION

7.1 pH, Hydroxide and Total Alkalinity

The pH, hydroxide and total alkalinity of all cement filtrates were reduced by interactions with the cores and also by reaction with the produced formation waters from Pelican Lake and West Edam (Synthetic formation waters were formulated to produce no precipitates when mixed with the cement filtrates).

API Class G + silica cement filtrate contained 1490 mg OH/L and 4330 mg/L total alkalinity as CaCO_3 (Table 9). However, the effluent from Pelican Lake core 4 (synthetic formation water) contained a maximum of only 476 mg OH/L and 1585 mg/L total alkalinity (Table 10 and Figure 9). Similarly West Edam core 2 effluent (synthetic formation water) contained a maximum of 855 mg OH/L and 2577 mg/L total alkalinity (Table 14 and Figure 13). Ciment Fondu filtrate contained 781 mg OH/L and 2010 mg/L alkalinity whereas the effluent from Pelican Lake core 5 contained a maximum of 160 mg OH/L and 931 mg/L total alkalinity (Tables 9 and 11 and Figure 10). Additional data are shown in Figures 11, 12 and 14. These decreases in alkalinity were not due to dilution with the synthetic formation water (Section 7.2).

Figures 15, 16 and 17 give a comparison of the pH, hydroxide and total alkalinity in effluents from core studies using synthetic and also produced formation waters. The hydroxide and total alkalinity concentrations are dramatically reduced in comparison to those of the injected cement filtrates (Tables 10 to 15).

Clay minerals are generally more compatible with low rather than high pH fluids (13). Not only are expandable clay minerals of concern, but problems of increased cleavage, or slaking reactions, of non-swelling clays occur as the water becomes more alkaline. Thus, even in formations that contain only illite and kaolinite, permeability reduction can occur with high pH fluids (14). Previous Gulf Canada R&D studies have shown that contact of heavy oil cores with low salinity or high pH fluids can result in a significant and often irreversible reduction in permeability (2).

7.2 Sodium and Chloride

API Class G + silica and Ciment Fondu cement filtrates contained chloride concentrations of only 65 and 45 mg/L respectively whereas the following waters contained high levels of chloride: Pelican Lake synthetic - 2900 mg/L, West Edam synthetic - 25 400 mg/L and West Edam produced - 35 000 mg/L (Tables 1,2 & 9). For the experiments using these waters, the chloride can be used to estimate the amount of water mixed with the cement filtrate in the core effluent. Since the chloride concentrations shown in Figure 19 are very low in comparison to those in the formation waters, the core effluents (pore volumes 3-10) were largely undiluted cement filtrates.

The sodium trends in the core effluents follow the chloride as shown in Figure 20. It is difficult to determine if ion exchange between the sodium and other metals is occurring since sodium is the major component in the waters.

7.3 Potassium and Sulfate

The main source of both potassium and sulfate in the experiments was the API Class G + silica cement filtrate with 6200 mg K/L and 6000 mg SO₄/L (Table 9). All waters as well as Ciment Fondu filtrate contained <15 mg SO₄/L (Tables 1 and 2).

The potassium/sulfate ratios decreased in core effluents (API Class G + silica) due to the interaction (as ion exchange) of the potassium with the cores, Tables 10, 13, 14 and 15 and Figures 18 and 21. (The sulfate increase in Pelican Lake core 7 effluents - pore volume 10 - may have been due to dissolution of traces of anhydrite in the alkaline fluid. Calcium also increased in concentration).

For reservoir damage prevention, potassium should be a valuable component of the cement filtrate since it increases the ionic strength and is a well known clay stabilizer.

7.4 Calcium and Aluminum

Calcium is a major component of both the API Class G + silica and Ciment Fondu filtrates at concentrations of 844 and 300 mg/L respectively (Table 9). The calcium interacts with the cores but the apparent traces of anhydrite in some Pelican Lake cores make the results difficult to interpret (Figure 22).

Aluminum is present in significant concentrations in Ciment Fondu filtrate, 260 mg/L, but virtually absent in API Class G + silica filtrate (Table 9). Aluminum, like potassium, is considered to be a clay stabilizer. However, in cement filtrates it is readily precipitated by mixing with some formation waters. Figure 23 shows the marked differences in aluminum concentrations in effluents from Pelican Lake cores flooded with synthetic formation water and produced formation water.

7.5 Magnesium

Magnesium was present in significant concentrations in only West Edam produced water, 580 mg/L (Table 1). Insoluble magnesium hydroxides form when this water is mixed with cement filtrates. Figure 24 shows the rapid decrease in magnesium concentration upon injection of a cement filtrate into a core flooded with West Edam produced water.

8. FLUID COMPATIBILITY

8.1 Compatibility of Cement Filtrates and Formation Waters - Procedures

The following combinations of cement filtrates and formation waters were studied:-

- (i) API Class G/Silica Flour + Pelican Lake Produced Formation Water
- (ii) Ciment Fondu + Pelican Lake Produced Formation Water
- (iii) API Class G/Silica Flour + West Edam Produced Formation Water
- (iv) Ciment Fondu + West Edam Produced Formation Water

The cement filtrates and produced formation waters were filtered to 0.45 μ and mixed in a 1:1 ratio in a nitrogen atmosphere. The precipitates formed were filtered under nitrogen, quantified and analyzed by inductively coupled plasma emission spectrometry. In addition the cement filtrates, formation waters and filtrates from the 1:1 mixtures were analyzed.

8.2 Compatibility of Cement Filtrates and Formation Water - Results

Ciment Fondu filtrate produced more precipitate than API Class G + silica filtrate when mixed with formation waters. The solids concentration from Ciment Fondu filtrate and produced water ranged from 1600 - 2750 mg/L for a 1:1 mixture whereas the concentration range for the API G + silica 1:1 mixture was 815 - 1150 mg/L (Table 16). The higher solids concentration from Ciment Fondu was due to the precipitation of aluminum compounds (Tables 16 and 17).

API Class G + silica when mixed with Pelican Lake formation water precipitated calcium probably as the carbonate (Tables 17 and 18). This cement filtrate when mixed with West Edam water precipitated both magnesium and calcium. The alkalinity of the 1:1 blend for West Edam was lowered to a greater extent than with Pelican Lake due to magnesium hydroxide precipitation (Table 19). When Ciment Fondu filtrate was mixed with these waters even greater drops in pH and alkalinity occurred (Tables 20 and 21). For West Edam and Ciment Fondu 1:1 blend, the hydroxide concentration became zero and the total alkalinity was only 84 mg/L.

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TABLE 1
ANALYSIS OF PELICAN LAKE AND
WEST EDAM PRODUCED FORMATION WATERS
(RESULTS IN MG/L)

	PELICAN LAKE WELL 12-16-81-22 W4M	WEST EDAM WELL 1C-31-48-20 W3M
pH (UNITS)	8.77	7.26
BICARBONATE	1308	375
CARBONATE	110	0
HYDROXIDE	0	0
pp ALKALINITY (AS CaCO_3)	92	0
TOTAL ALKALINITY (AS CaCO_3)	1256	308
CHLORIDE	180	35 000
SULFATE	12	<10
SODIUM	700	19 300
POTASSIUM	40.6	380
CALCIUM	2.82	490
MAGNESIUM	1.21	580
ALUMINUM	0.05	<0.01
BARIUM	0.12	23.6
BERYLLIUM	<0.001	<0.001
BORON	4.00	8.64
CADMIUM	0.003	<0.001
CHROMIUM	<0.001	<0.001
COBALT	0.006	<0.001
COPPER	0.005	0.001
IRON	0.04	0.01
LEAD	<0.01	0.02
LITHIUM	0.087	4.84
MANGANESE	0.004	0.027
MOLYBDENUM	0.008	0.036
NICKEL	<0.001	0.022
SILICON	2.09	4.47
STRONTIUM	0.25	54.7
VANADIUM	0.003	0.003
ZINC	0.24	0.018

TABLE 2
ANALYSIS OF PELICAN LAKE AND
WEST EDAM SYNTHETIC FORMATION WATERS
(RESULTS IN MG/L)

	PELICAN LAKE	WEST EDAM
pH (UNITS)	6.85	6.67
BICARBONATE	10	20
CARBONATE	0	0
HYDROXIDE	0	0
pp ALKALINITY (AS CaCO_3)	0	0
TOTAL ALKALINITY (AS CaCO_3)	8.2	16.4
CHLORIDE	2900	25 400
SULFATE	<1	<1
SODIUM	1850	15 840
POTASSIUM	110	247
CALCIUM	0.30	0.91
MAGNESIUM	<0.01	0.30
ALUMINUM	0.22	<0.01
BARIUM	0.01	0.02
BERYLLIUM	0.004	0.003
BORON	<0.01	0.09
CADMIUM	0.085	0.026
CHROMIUM	0.049	0.30
COBALT	<0.001	0.057
COPPER	0.053	0.054
IRON	<0.01	0.16
LEAD	0.87	0.29
LITHIUM	<0.001	<0.001
MANGANESE	0.016	<0.004
MOLYBDENUM	<0.001	0.21
NICKEL	0.11	0.29
SILICON	0.03	0.09
STRONTIUM	0.012	0.026
VANADIUM	0.013	0.048
ZINC	0.016	0.010

TABLE 3
ANALYSIS OF LAKE WATER USED
FOR MIXING OF CEMENTS
(RESULTS IN MG/L)

pH (UNITS)	8.01
BICARBONATE	121
CARBONATE	0
HYDROXIDE	0
pp ALKALINITY (AS CaCO_3)	0
TOTAL ALKALINITY (AS CaCO_3)	99.0
CHLORIDE	30
SULFATE	34
SODIUM	13.0
POTASSIUM	1.33
CALCIUM	41.0
MAGNESIUM	8.2
ALUMINUM	0.16
BARIUM	0.02
BERYLLIUM	<0.001
BORON	0.02
CADMIUM	<0.001
CHROMIUM	<0.001
COBALT	0.008
COPPER	0.002
IRON	<0.001
LEAD	<0.01
LITHIUM	0.001
MANGANESE	<0.004
MOLYBDENUM	0.009
NICKEL	0.005
SILICON	0.48
STRONTIUM	0.18
VANADIUM	0.002
ZINC	0.004

TABLE 4
FORMULATION OF CEMENTS

API CLASS G + SILICA FLOUR

750 g API Class G (a)

250 g Silica Flour(b)

466 mL Water

CEMENT FONDU

1000 g Ciment Fondu (a)

466 mL Water

(a) Available from Canada Cement Lafarge Ltd.

(b) Available from Halliburton Services Ltd.

TABLE 5
CORE DISPLACEMENT EXPERIMENTS

<u>CORE</u>	<u>CEMENT FILTRATE</u>	<u>WATER</u>
PELICAN LAKE 4	API Class G + Silica Flour	Synthetic Pelican Lake
PELICAN LAKE 5	Ciment Fondu	Synthetic Pelican Lake
PELICAN LAKE 6	Ciment Fondu	Produced Pelican Lake
PELICAN LAKE 7	API Class G + Silica Flour	Produced Pelican Lake
WEST EDAM 2	API Class G + Silica Flour	Synthetic West Edam
WEST EDAM 3	Ciment Fondu	Synthetic West Edam
WEST EDAM 4	API Class G + Silica Flour	Produced West Edam
WEST EDAM 5	Ciment Fondu	Produced West Edam

TABLE 6
PHYSICAL DATA ON PELICAN LAKE AND
WEST EDAM CORES USED FOR PERMEABILITY STUDIES

	LENGTH cm	DIAMETER cm	POROSITY
PELICAN LAKE CORE 4	6.40	2.54	10.5
PELICAN LAKE CORE 5	6.90	2.54	12.1
PELICAN LAKE CORE 6	6.40	2.54	10.5
PELICAN LAKE CORE 7	3.60	2.54	7.8
WEST EDAM CORE 2	6.70	2.54	11.2
WEST EDAM CORE 3	6.20	2.54	6.8
WEST EDAM CORE 4	6.40	2.54	10.0
WEST EDAM CORE 5	6.00	2.54	10.2

TABLE 7

PHYSICAL PROPERTIES OF FLUIDS
USED FOR PERMEABILITY STUDIES

	PELICAN LAKE SYNTHETIC FORMATION WATER	PELICAN LAKE PRODUCED FORMATION WATER	WEST EDAM SYNTHETIC FORMATION WATER	WEST EDAM PRODUCED FORMATION WATER	API CLASS G + SILICA CEMENT FILTRATE	CEMENT FONDU FILTRATE
Viscosity cP @ 25C	1.00	0.890	0.924	0.976	0.940	0.930
Density @ 15C	1.0401	0.9980	1.0304	1.0388	1.0101	1.0017

TABLE 8

CORE DISPLACEMENT RESULTS

CORE	CEMENT FILTRATE	WATER	WATER PERMEABILITY mD	PERMEABILITY CEMENT FILTRATE mD	PERMEABILITY WATER mD	PERMEABILITY DECREASE %
PELICAN LAKE 4	API Class G + Silica	Synthetic	682	375	661	3.08
PELICAN LAKE 5	Ciment Fondu	Synthetic	908	598	743	18.2
PELICAN LAKE 6	Ciment Fondu	Produced Formation	973	1067	976	0
PELICAN LAKE 7	API Class G + Silica	Produced Formation	225	102	49	78.2
WEST EDAM 2	API Class G + Silica	Synthetic	974	430	610	37.4
WEST EDAM 3	Ciment Fondu	Synthetic	548	508	459	16.2
WEST EDAM 4	API Class G + Silica	Produced Formation	1354	709	887	34.5
WEST EDAM 5	Ciment Fondu	Produced Formation	1272	561	656	48.4

TABLE 9

ANALYSIS OF FILTRATES FROM API CLASS G WITH
SILICA FLOUR AND CIMENT FONDU OIL WELL CEMENTS
(RESULTS IN MG/L)

	API CLASS G WITH SILICA FLOUR	CIMENT FONDU
pH (UNITS)	12.09	11.23
BICARBONATE	0	0
CARBONATE	42	174
HYDROXIDE	1490	781
pp ALKALINITY (AS CaCO_3)	4260	1720
TOTAL ALKALINITY (AS CaCO_3)	4330	2010
CHLORIDE	65	45
SULFATE	6000	0
SODIUM	370	62.6
POTASSIUM	6200	187
CALCIUM	844	300
MAGNESIUM	0.59	0.14
ALUMINUM	0.22	260
BARIUM	0.61	0.36
BERYLLIUM	0.001	<0.001
BORON	0.12	0.27
CADMIUM	0.030	0.003
CHROMIUM	6.71	<0.001
COBALT	0.027	0.011
COPPER	0.038	<0.001
IRON	0.10	0.03
LEAD	0.30	0.08
LITHIUM	0.12	0.004
MANGANESE	0.006	<0.004
MOLYBDENUM	0.60	0.44
NICKEL	0.087	0.007
SILICON	1.84	0.39
STRONTIUM	5.63	27.9
VANADIUM	0.042	0.011
ZINC	0.028	0.014

TABLE 10

PELICAN LAKE CORE 4 EFFLUENT ANALYSIS
API CLASS G + SILICA FLOUR WITH SYNTHETIC FORMATION WATER
(RESULTS IN MG/L)

PORE VOLUMES	CEMENT FILTRATE EFFLUENT				WATER EFFLUENT	
	1	2	3	7	10	1 2
pH (UNITS)	7.25	10.96	11.46	11.44	11.53	11.73 11.48
BICARBONATE	74.9	0	0	0	0	0 0
CARBONATE	0	172	73	209	73	110 97
HYDROXIDE	0	83	365	320	327	476 369
PP ALKALINITY (AS CaCO ₃)	0	388	1135	1114	1023	1493 1166
TOTAL ALKALINITY (AS CaCO ₃)	61.4	532	1196	1288	1084	1585 1247
CHLORIDE	1900	420	214	114	86	84 1460
SULFATE	3200	6360	5880	6050	5920	6250 4140
SODIUM	1660	645	476	370	317	315 840
POTASSIUM	1380	3570	3950	4345	4410	4400 2840
CALCIUM	215	639	1065	585	555	1090 701
MAGNESIUM	0.69	0.57	0.70	0.54	2.52	1.35 0.80
ALUMINUM	0.58	0.92	0.61	0.13	0.37	0.89 0.31
BARIUM	0.13	0.19	0.24	0.18	0.19	0.17 0.25
BERYLLIUM	0.001	0.002	0.004	0.002	0.006	0.003 0.001
BORON	<0.01	<0.01	<0.01	0.13	<0.01	<0.01 <0.01
CADMIUM	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001 <0.001
CHROMIUM	2.27	4.77	5.11	5.37	5.62	5.59 3.19
COBALT	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001 0.009
COPPER	0.060	0.072	0.11	0.12	0.13	0.12 0.076
IRON	0.12	0.30	0.17	0.17	0.17	0.16 0.10
LEAD	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01 <0.01
LITHIUM	0.036	0.060	0.10	0.11	0.19	0.16 0.19
MANGANESE	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004 <0.004
MOLYBDENUM	0.15	0.40	0.40	0.41	0.48	0.50 0.30
NICKEL	0.23	0.14	0.16	<0.001	0.053	0.16 <0.001
SILICON	0.42	1.55	0.79	1.54	0.78	1.26 1.18
STRONTIUM	1.20	3.82	3.80	4.42	4.37	4.25 3.23
VANADIUM	0.029	<0.001	0.040	0.041	0.091	0.086 0.043
ZINC	0.11	<0.001	0.031	0.044	0.047	0.056 0.051

TABLE 11

PELICAN LAKE CORE 5 EFFLUENT ANALYSIS
CIMENT FONDU WITH SYNTHETIC PELICAN LAKE WATER
(RESULTS IN MG/L)

PORE VOLUMES	CEMENT FILTRATE EFFLUENT			WATER EFFLUENT	
	1	2	3	7	10
pH (UNITS)	10.53	10.49	11.16	10.46	12.20
BICARBONATE	0	0	0	0	0
CARBONATE	146	258	270	246	172
HYDROXIDE	28.2	170	136	160	148
PP ALKALINITY (AS CaCO_3)	205	716	624	675	90.4
TOTAL ALKALINITY (AS CaCO_3)	327	931	849	880	389
CHLORIDE	370	178	119	53	512
SULFATE	14	2	2	<1.0	1200
					<1
SODIUM	408	400	275	93.0	545
POTASSIUM	14.7	85	159	180	200
CALCIUM	0.16	13.1	2.89	133	79.2
MAGNESIUM	<0.01	<0.01	<0.01	<0.02	99.5
					0.10
ALUMINUM	12.5	140	120	288	81.1
BARIUM	0.01	0.02	0.03	0.06	70.8
BERYLLIUM	0.038	0.002	0.007	0.003	0.20
BORON	<0.01	<0.01	<0.01	<0.01	0.007
CADMIUM	<0.001	<0.001	0.076	0.032	0.53
CHROMIUM	<0.001	0.024	0.023	<0.001	0.052
COBALT	0.088	<0.001	0.001	0.014	0.031
COPPER	0.065	0.043	0.034	0.037	<0.001
IRON	<0.001	0.10	0.09	0.11	0.040
LEAD	0.79	0.07	<0.01	2.49	0.18
LITHIUM	<0.001	<0.001	<0.001	<0.01	0.18
MANGANESE	<0.004	0.016	0.010	0.020	<0.001
MOLYBDENUM	0.13	0.42	0.33	0.70	0.012
NICKEL	0.42	0.074	0.092	0.063	0.16
SILICON	0.09	0.27	0.25	0.42	0.11
STRONTIUM	0.004	0.13	0.25	0.96	0.32
VANADIUM	<0.001	0.065	0.021	0.026	1.66
ZINC	<0.001	<0.001	0.011	<0.001	0.053
					0.056

TABLE 12

PELICAN LAKE CORE 6 EFFLUENT ANALYSIS
CIMENT FONDU WITH PRODUCED FORMATION WATER
(RESULTS IN MG/L)

PORE VOLUMES	CEMENT FILTRATE EFFLUENT						WATER EFFLUENT	
	1	2	3	7	10		1	2
pH (UNITS)	9.20	9.23	10.04	10.35	10.26		10.67	11.20
BICARBONATE	1350	961	0	0	0		0	0
CARBONATE	109	148	221	270	148		197	197
HYDROXIDE	0	0	69.7	111	55.4		69.4	125
DP ALKALINITY (AS CaCO_3)	91.1	123	389	552	286		368	532
TOTAL ALKALINITY (AS CaCO_3)	1290	1080	573	777	409		532	696
CHLORIDE	172	162	52	35	25		28	46
SULFATE	7	15	28	33	6		3	7
SODIUM	635	530	277	105	53.5		53.1	88.0
POTASSIUM	51	44	22.1	150	152		145	132
CALCIUM	4.00	2.74	0.15	99.3	112		120	92.1
MAGNESIUM	1.94	1.42	<0.01	0.09	<0.01		<0.01	<0.01
ALUMINUM	0.57	7.48	36.2	26.5	75.4		83.0	80.5
BARIUM	0.10	0.09	0.02	0.30	0.42		0.39	0.37
BERYLLIUM	0.007	0.005	0.005	0.005	<0.001		<0.001	<0.001
BORON	4.77	4.58	2.32	1.34	0.43		0.39	0.53
CADMIUM	0.060	0.053	0.035	0.014	0.039		<0.001	0.014
CHROMIUM	0.055	0.030	0.092	0.028	0.074		0.019	<0.001
COBALT	0.010	0.007	0.070	0.072	0.037		<0.001	0.065
COPPER	0.083	0.061	0.054	0.036	0.025		0.021	0.020
IRON	0.15	0.13	0.12	0.14	0.07		0.11	0.19
LEAD	0.62	<0.01	<0.01	1.10	1.00		0.78	<0.11
LITHIUM	0.049	0.043	<0.001	<0.001	<0.001		<0.001	<0.001
MANGANESE	0.016	0.009	0.022	0.012	0.006		<0.004	0.010
MOLYBDENUM	0.005	0.012	0.061	0.68	0.15		0.18	0.27
NICKEL	<0.001	0.39	0.19	0.046	0.027		<0.001	0.23
SILICON	2.69	1.57	0.48	0.42	0.33		0.31	0.33
STRONTIUM	0.28	0.21	0.046	1.93	1.67		1.49	1.16
VANADIUM	0.048	0.033	0.046	0.044	0.040		0.016	0.035
ZINC	<0.001	<0.001	<0.001	0.046	0.021		0.008	<0.001

TABLE 13

PELICAN LAKE CORE 7 EFFLUENT ANALYSIS
API CLASS 6 + SILICA WITH PRODUCED FORMATION WATER
(RESULTS IN MG/L)

PORE VOLUMES	CEMENT FILTRATE EFFLUENT						WATER EFFLUENT	
	1	2	3	7	10		1	2
pH (UNITS)	9.22	9.00	8.29	11.45	12.20		12.16	12.20
BICARBONATE	98.2	98.2	0	0	0		0	0
CARBONATE	1330	1160	150	148	184		172	270
HYDROXIDE	0	0	0	115	811		772	758
PP ALKALINITY (AS CaCO ₃)	81.8	81.8	0	460	2540		2410	2460
TOTAL ALKALINITY (AS CaCO ₃)	1290	1150	123	583	2690		2560	2680
CHLORIDE	180	154	65	60	50		60	58
SULFATE	10	482	4130	6100	7700		7100	6750
SODIUM	615	700	667	295	390		385	350
POTASSIUM	50	130	2100	3800	5300		5100	4800
CALCIUM	3.96	10.2	215	521	840		940	890
MAGNESIUM	1.62	4.86	23.3	<0.01	0.02		<0.01	<0.01
ALUMINUM	0.01	0.13	0.25	0.37	0.13		<0.01	<0.01
BARIUM	0.07	0.28	0.10	0.34	0.32		0.33	0.31
BERYLLIUM	<0.001	<0.001	<0.001	<0.001	<0.001		<0.001	<0.001
BORON	4.56	4.14	1.79	0.74	<0.01		0.01	0.11
CADMIUM	<0.001	<0.001	0.022	<0.001	0.033		<0.001	0.004
CHROMIUM	<0.001	0.28	2.66	3.75	5.85		5.63	5.24
COBALT	0.078	0.027	<0.001	<0.001	0.14		<0.001	<0.011
COPPER	0.057	0.29	0.032	0.093	0.079		0.049	0.045
IRON	0.12	0.24	0.13	0.14	0.13		0.17	0.17
LEAD	0.58	0.11	0.30	0.51	0.05		<0.01	0.54
LITHIUM	0.084	0.11	0.073	<0.001	0.053		0.052	0.047
MANGANESE	0.035	0.021	0.036	0.010	0.006		<0.004	0.010
MOLYBDENUM	0.009	0.11	0.22	0.42	0.53		0.42	0.43
NICKEL	0.086	0.28	0.19	<0.001	<0.001		<0.001	<0.001
SILICON	2.63	2.63	3.76	3.75	0.63		0.62	0.81
STRONTIUM	0.23	0.74	6.28	5.23	7.27		7.09	6.66
VANADIUM	0.014	0.011	0.044	0.055	0.038		<0.001	0.012
ZINC	<0.001	<0.001	0.085	<0.001	0.022		0.015	0.032

TABLE 14

WEST EDAM CORE 2 EFFLUENT ANALYSIS
API CLASS G + SILICA WITH SYNTHETIC FORMATION WATER
(RESULTS IN MG/L)

PORE VOLUMES	CEMENT FILTRATE EFFLUENT				WATER EFFLUENT	
	1	2	3	7	1	2
pH (UNITS)	6.65	9.91	11.43	11.66	11.83	11.71
BICARBONATE	25.0	36.8	0	0	0	0
CARBONATE	0	49.1	172	146	24.0	122
HYDROXIDE	0	0	494	758	855	689
pp ALKALINITY (AS CaCO_3)	0	40.9	1595	2352	2536	2127
TOTAL ALKALINITY (AS CaCO_3)	20.5	112	1738	2474	2556	2229
CHLORIDE	27 500	22 800	4200	560	460	5000
SULFATE	<1	1100	4800	5560	5700	4700
SODIUM	17 200	14 100	2930	610	526	3380
POTASSIUM	325	830	2620	4510	4540	4025
CALCIUM	6.20	30.0	475	680	775	725
MAGNESIUM	2.20	0.49	0.54	0.52	0.54	0.60
ALUMINUM	0.17	0.78	2.23	3.1	0.02	0.34
BARIUM	0.87	0.10	0.19	0.23	0.20	0.24
BERYLLIUM	0.006	0.007	<0.001	<0.001	0.002	0.004
BORON	<0.01	<0.01	0.91	1.43	<0.01	<0.01
CADMIUM	0.001	<0.001	<0.001	<0.001	<0.001	<0.001
CHROMIUM	0.082	1.10	5.31	5.77	6.10	5.08
COBALT	<0.001	<0.001	0.32	<0.001	0.002	<0.001
COPPER	0.035	0.055	0.12	0.12	0.007	0.099
IRON	0.14	0.24	0.39	0.20	0.08	0.17
LEAD	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
LITHIUM	0.090	0.037	0.024	0.013	0.24	0.23
MANGANESE	0.19	0.007	<0.004	<0.004	<0.004	<0.004
MOLYBDENUM	<0.001	0.13	0.41	0.45	0.66	0.34
NICKEL	1.12	0.34	<0.001	<0.001	0.027	0.13
SILICON	0.39	0.72	1.65	0.88	0.50	1.26
STRONTIUM	0.065	0.41	4.37	6.40	6.39	5.70
VANADIUM	0.021	0.056	0.038	0.045	<0.001	0.051
ZINC	0.077	0.008	0.045	0.057	0.006	0.037

TABLE 15

WEST EDAM CORE 4 EFFLUENT ANALYSIS
API CLASS G + SILICA WITH PRODUCED WEST EDAM FORMATION WATER
(RESULTS IN MG/L)

PORE VOLUMES	CEMENT FILTRATE EFFLUENT							WATER EFFLUENT	
	1	2	3	7	10			1	2
pH (UNITS)	8.15	8.08	12.25	12.22	11.97			12.20	11.87
BICARBONATE	174	256	0	0	0			0	0
CARBONATE	0	0	282	233	258			295	614
HYDROXIDE	0	0	355	689	629			284	181
PP ALKALINITY (AS CaCO ₃)	0	0	1280	2220	2070			1080	1043
TOTAL ALKALINITY (AS CaCO ₃)	143	312	1510	2410	2280			1330	1560
CHLORIDE	34 100	26 000	970	780	74			40	8800
SULFATE	<1	1180	5700	5700	4920			5400	5600
SODIUM	19 800	17 000	1033	620	285			290	5400
POTASSIUM	340	718	4500	4850	4020			4000	3400
CALCIUM	420	416	630	625	610			650	1030
MAGNESIUM	580	440	0.44	0.25	0.17			<0.01	16.7
ALUMINUM	0.08	0.02	0.22	0.16	0.02			<0.01	0.02
BARIUM	27.3	0.30	0.87	0.16	0.23			0.13	0.71
BERYLLIUM	0.008	<0.001	<0.001	<0.001	<0.001			<0.001	<0.001
BORON	10.1	9.36	1.10	1.83	<0.01			<0.01	0.31
CADMIUM	<0.001	0.013	<0.001	0.030	<0.001			0.056	0.025
CHROMIUM	0.019	0.85	6.67	6.40	5.53			5.63	4.00
COBALT	0.12	<0.001	0.009	0.067	0.005			0.12	0.18
COPPER	0.042	0.052	0.084	0.078	0.071			0.051	0.063
IRON	0.09	0.04	0.08	0.06	0.15			0.17	0.10
LEAD	0.28	0.68	0.41	0.18	0.28			0.96	1.06
LITHIUM	5.30	4.63	0.23	0.18	0.11			0.12	1.33
MANGANESE	0.022	0.019	0.007	0.010	0.005			0.013	0.005
MOLYBDENUM	0.12	0.21	0.63	0.60	0.46			0.61	0.47
NICKEL	0.21	0.15	<0.001	0.11	0.12			0.18	0.25
SILICON	4.85	4.58	1.69	0.94	0.79			0.81	2.05
STRONTIUM	50.4	41.6	8.20	7.07	5.27			5.53	14.4
VANADIUM	0.020	0.032	0.030	0.023	<0.001			0.020	0.023
ZINC	0.009	<0.001	<0.001	<0.001	0.013			<0.001	<0.001

TABLE 16

PRECIPITATES FORMED BY MIXING
CEMENT FILTRATES WITH FORMATION WATERS

	APIG/ PELICAN LAKE 50:50	APIG/ WEST EDAM 50:50	CIMENT FONDU/ PELICAN LAKE 50:50	CIMENT FONDU/ WEST EDAM 50:50
PRECIPITATE, mg	228	322	448	770
COMBINED VOLUME, mL	280	280	280	280
SOLIDS, mg/L	815	1150	1600	2750
MAJOR COMPONENTS OF PRECIPITATE	Calcium	Magnesium Calcium	Calcium Aluminum	Aluminum Magnesium Calcium

TABLE 17

MAJOR AND MINOR ELEMENTS IN PRECIPITATES
FORMED BY MIXING CEMENT FILTRATES
WITH FORMATION WATERS

	APIG + SiO ₂ / PELICAN LAKE WT. %	APIG + SiO ₂ / WEST EDAM ² / WT. %	CIMENT FONDU/ PELICAN LAKE WT. %	CIMENT FONDU/ WEST EDAM WT. %
SODIUM	0.39	1.59	0.24	2.11
POTASSIUM	0.55	0.48	0.05	0.06
CALCIUM	30.0	8.48	23.4	2.68
MAGNESIUM	0.10	21.0	0.09	9.39
ALUMINUM	0.05	0.03	12.6	18.5
BARIUM	0.03	0.43	0.01	0.02
BORON	0.01	0.02	0.01	0.07
IRON	0.03	0.12	0.01	0.00
MOLYBDENUM	0.00	0.00	0.02	0.03
SILICON	0.03	0.08	0.05	0.01
STRONTIUM	0.21	0.14	0.06	0.02
ZINC	0.02	0.00	0.01	0.00

TABLE 18

COMPATIBILITY OF CEMENT FILTRATES WITH FORMATION WATERS
API CLASS 6 + SILICA FILTRATE AND PELICAN LAKE WATER
(RESULTS IN MG/L)

	PELICAN LAKE FORMATION WATER	APIG + SILICA CEMENT FILTRATE	50% APIG + SILICA & 50% PELICAN LAKE AFTER FILTRATION	COMPOSITION OF PRECIPITATE mg/Kg
pH (UNITS)	8.77	12.09	11.68	-
BICARBONATE	1308	0	0	-
CARBONATE	110	42	96	-
HYDROXIDE	0	1490	509	-
PP ALKALINITY (AS CaCO ₃)	92	4260	1660	-
TOTAL ALKALINITY (AS CaCO ₃)	1256	4330	1820	-
CHLORIDE	180	65	110	-
SULFATE	12	6000	2980	-
SODIUM	700	370	540	3870
POTASSIUM	40.6	6200	3075	5540
CALCIUM	2.82	844	13.2	300 000
MAGNESIUM	1.21	0.59	0.11	975
ALUMINUM	0.05	0.22	0.46	460
BARIUM	0.12	0.61	0.03	338
BERYLLIUM	<0.001	0.001	<0.001	<0.01
BORON	4.00	0.12	2.26	55
CADMIUM	0.003	0.030	0.020	<0.01
CHROMIUM	<0.001	6.71	3.22	13.1
COBALT	0.006	0.027	0.014	4.44
COPPER	0.005	0.038	0.015	17.5
IRON	0.04	0.10	0.09	300
LEAD	<0.01	0.30	0.05	27.0
LITHIUM	0.087	0.12	0.10	3.3
MANGANESE	0.004	0.006	<0.004	7.0
MOLYBDENUM	0.008	0.60	0.24	11.5
NICKEL	<0.001	0.087	0.036	43.6
SILICON	2.09	1.84	2.06	253
STRONTIUM	0.25	5.63	0.75	2120
VANADIUM	0.003	0.042	0.015	1.80
ZINC	0.24	0.028	0.016	173

TABLE 19

COMPATIBILITY OF CEMENT FILTRATES WITH FORMATION WATERS
API CLASS G + SILICA FILTRATE AND WEST EDAM WATER
(RESULTS IN MG/L)

	WEST EDAM FORMATION WATER	APIG + SILICA CEMENT FILTRATE	50% APIG + SILICA & 50% WEST EDAM AFTER FILTRATION	COMPOSITION OF PRECIPITATE mg/Kg
pH (UNITS)	7.26	12.09	11.10	-
BICARBONATE	375	0	0	-
CARBONATE	0	42	36	-
HYDROXIDE	0	1490	256	-
pp ALKALINITY (AS CaCO ₃)	0	4260	636	-
TOTAL ALKALINITY (AS CaCO ₃)	308	4330	696	-
CHLORIDE	35 000	65	17 000	-
SULFATE	<10	6000	2600	-
SODIUM	19 300	370	10 500	15 900
POTASSIUM	380	6200	3100	4770
CALCIUM	490	844	490	84 800
MAGNESIUM	580	0.59	0.29	210 300
ALUMINUM	<0.01	0.22	0.09	326
BARIUM	23.6	0.61	0.27	4280
BERYLLIUM	<0.001	0.001	<0.001	0.11
BORON	8.64	0.12	4.21	173
CADMIUM	<0.001	0.030	0.012	<0.01
CHROMIUM	<0.001	6.71	2.82	20.9
COBALT	<0.001	0.027	<0.001	15.7
COPPER	0.001	0.038	0.008	10.2
IRON	0.01	0.10	0.03	153
LEAD	0.02	0.30	0.06	31.8
LITHIUM	4.84	0.12	2.16	7.33
MANGANESE	0.021	0.006	<0.004	15.1
MOLYBDENUM	0.036	0.60	0.24	38.1
NICKEL	0.022	0.087	0.18	24.2
SILICON	4.47	1.84	0.39	810
STRONTIUM	54.7	5.63	27.9	1360
VANADIUM	0.003	0.042	0.011	1.48
ZINC	0.018	0.028	0.014	35.3

TABLE 20

COMPATIBILITY OF CEMENT FILTRATES WITH FORMATION WATERS
CIMENT FONDU FILTRATE AND PELICAN LAKE FORMATION WATER
(RESULTS IN MG/L)

	PELICAN LAKE FORMATION WATER	CIMENT FONDU FILTRATE	50% CIMENT FONDU & 50% PELICAN LAKE AFTER FILTRATION	COMPOSITION OF PRECIPITATE mg/Kg
pH (UNITS)	8.77	11.23	9.90	-
BICARBONATE	1308	0	0	-
CARBONATE	110	174	139	-
HYDROXIDE	0	781	154	-
pp ALKALINITY (AS CaCO_3)	92	1720	686	-
TOTAL ALKALINITY (AS CaCO_3)	1256	2010	918	-
CHLORIDE	180	45	120	-
SULFATE	12	0	10	-
SODIUM	700	62.6	392	2400
POTASSIUM	40.6	187	105	540
CALCIUM	2.82	300	2.11	233 500
MAGNESIUM	1.21	0.14	0.03	900
ALUMINUM	0.05	260	65	126 000
BARIUM	0.12	0.36	<0.01	130
BERYLLIUM	<0.001	<0.001	<0.001	<0.01
BORON	4.00	0.27	2.30	104
CADMIUM	0.003	0.003	<0.001	<0.01
CHROMIUM	<0.001	<0.001	<0.001	4.48
COBALT	0.006	0.011	<0.001	3.51
COPPER	0.005	<0.001	<0.001	7.63
IRON	0.04	0.03	0.02	112
LEAD	<0.01	0.08	0.03	19.2
LITHIUM	0.087	0.004	0.049	4.95
MANGANESE	0.004	<0.004	<0.004	4.20
MOLYBDENUM	0.008	0.44	0.66	237
NICKEL	<0.001	0.007	<0.001	18.5
SILICON	2.09	0.39	0.23	510
STRONTIUM	0.25	27.9	0.023	604
VANADIUM	0.003	0.011	0.002	0.87
ZINC	0.24	0.014	<0.001	110

TABLE 21

COMPATIBILITY OF CEMENT FILTRATES WITH FORMATION WATERS
CIMENT FONDU FILTRATE AND WEST EDAM FORMATION WATER
(RESULTS IN MG/L)

	WEST EDAM FORMATION WATER	CIMENT FONDU FILTRATE	50% CIMENT FONDU & 50% WEST EDAM AFTER FILTRATION	COMPOSITION OF PRECIPITATE mg/Kg
pH (UNITS)	7.26	11.23	8.92	-
BICARBONATE	375	0	29.3	-
CARBONATE	0	174	36	-
HYDROXIDE	0	781	0	-
pp ALKALINITY (AS CaCO_3)	0	1720	30	-
TOTAL ALKALINITY (AS CaCO_3)	308	2010	84	-
CHLORIDE	35 000	45	17 000	-
SULFATE	<10	0	<1	-
SODIUM	19 300	62.6	10 500	21 100
POTASSIUM	380	187	315	600
CALCIUM	490	300	540	26 800
MAGNESIUM	580	0.14	12.5	93 900
ALUMINUM	<0.01	260	6.18	185 000
BARIUM	23.6	0.36	12.1	165
BERYLLIUM	<0.001	<0.001	<0.001	<0.01
BORON	8.64	0.27	2.83	650
CADMIUM	<0.001	0.003	<0.001	0.74
CHROMIUM	<0.001	<0.001	<0.001	2.46
COBALT	<0.001	0.011	<0.001	1.63
COPPER	0.001	<0.001	<0.001	1.46
IRON	0.01	0.03	0.01	40
LEAD	0.02	0.08	<0.01	46.9
LITHIUM	4.84	0.004	0.021	855
MANGANESE	0.027	<0.004	<0.004	14.0
MOLYBDENUM	0.036	0.44	0.037	335
NICKEL	0.022	0.007	<0.005	<0.1
SILICON	4.47	0.39	0.21	114
STRONTIUM	54.7	27.9	28.5	234
VANADIUM	0.003	0.011	<0.001	0.10
ZINC	0.018	0.014	0.007	13.6

FIGURE 1A

EFFECT OF CLASS G CEMENT FILTRATE ON PELICAN #4

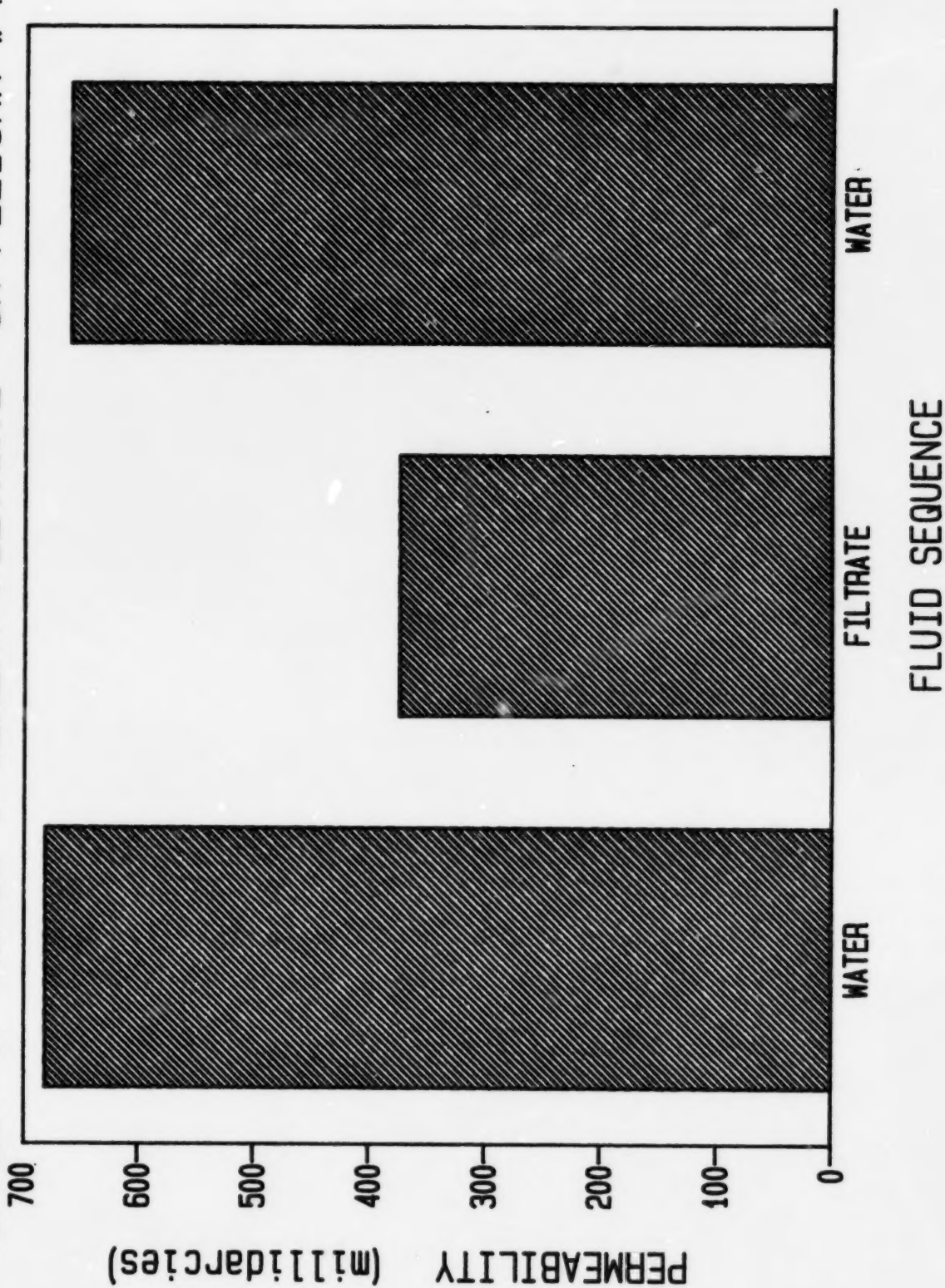


FIGURE 1B

DARCY REGIME FOR PELICAN CORE 4

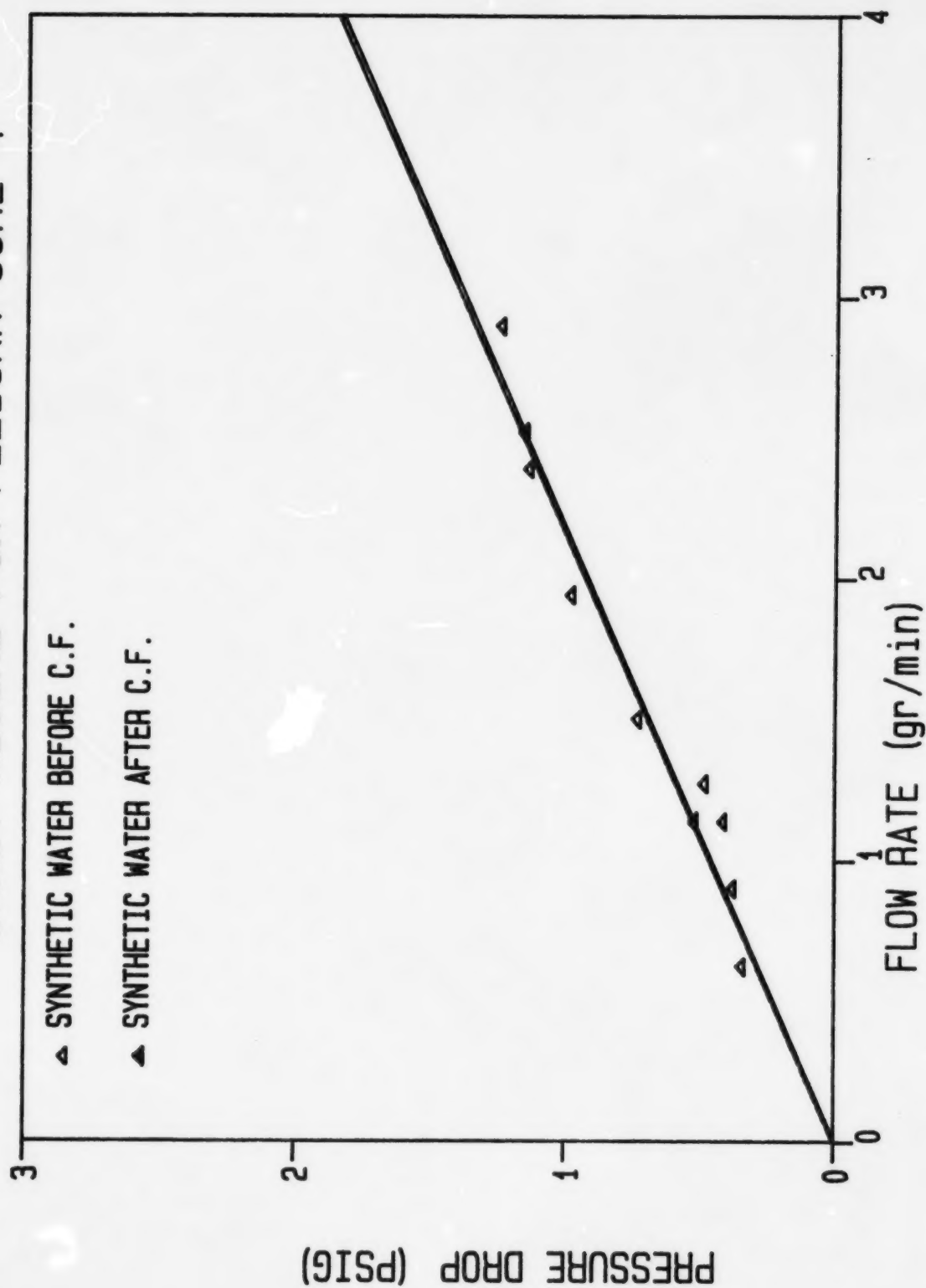


FIGURE 2A

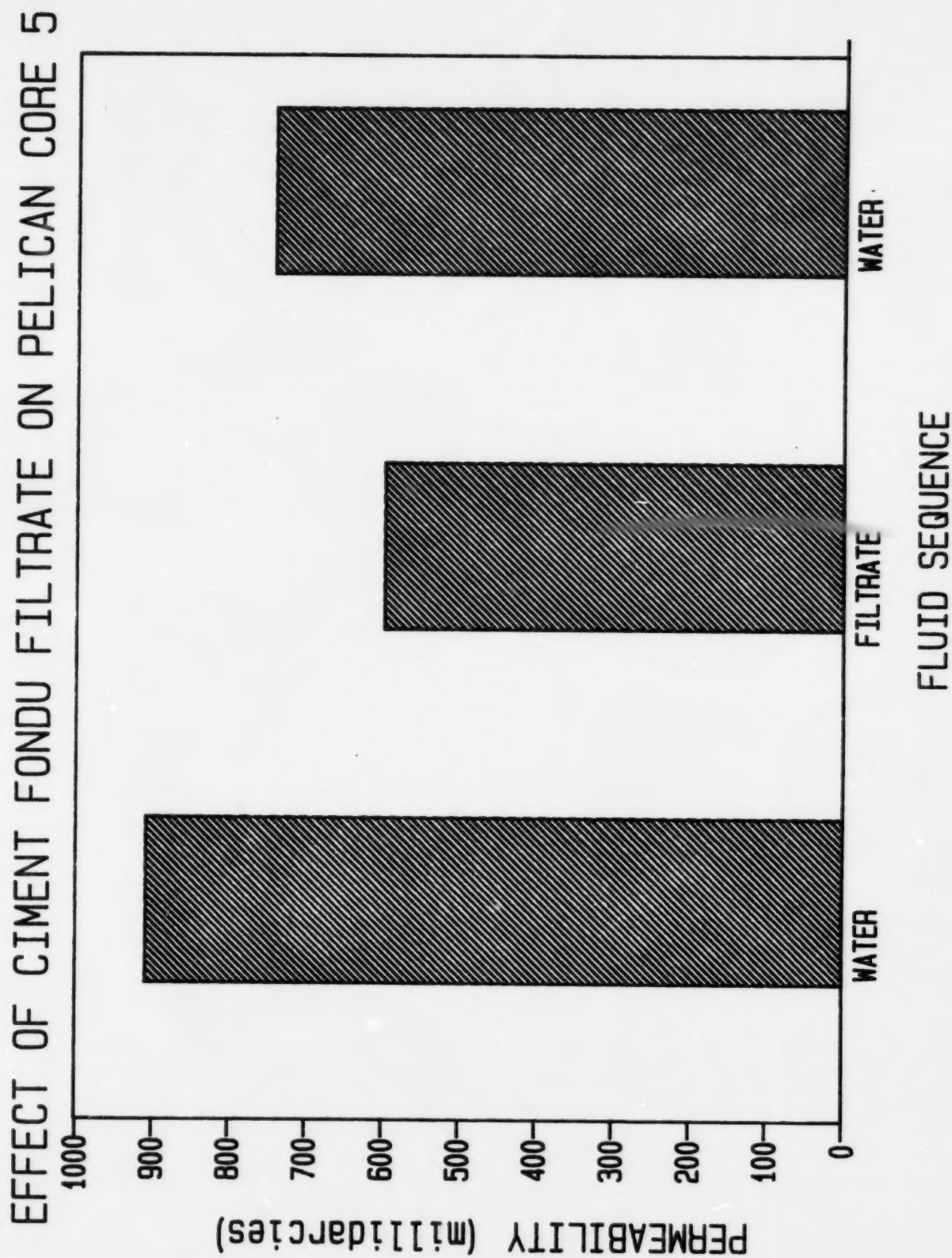


FIGURE 2B

DARCY REGIME FOR PELICAN CORE 5

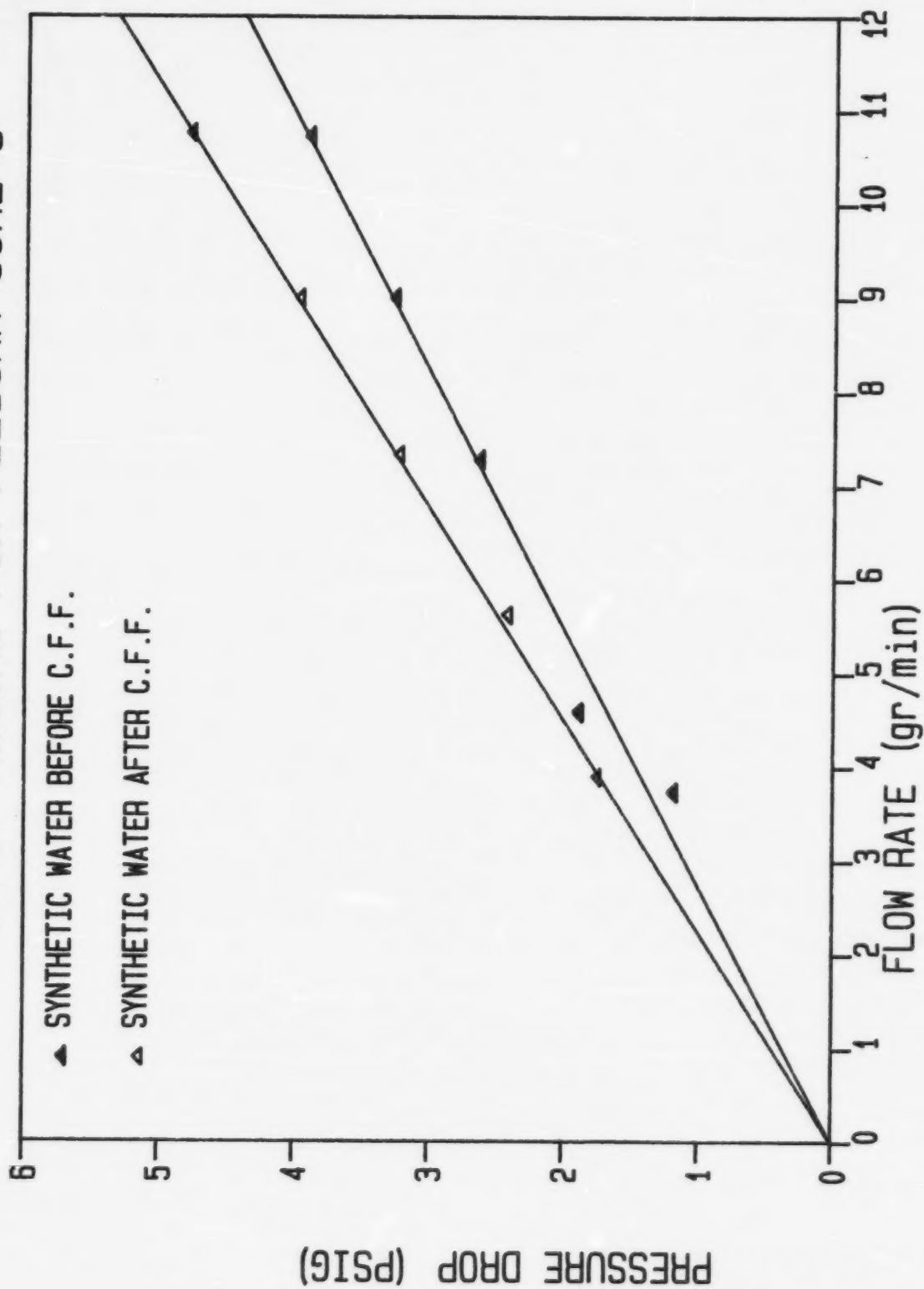


FIGURE 3A

EFFECT OF CEMENT FONDU FILTRATE ON PELICAN CORE 6

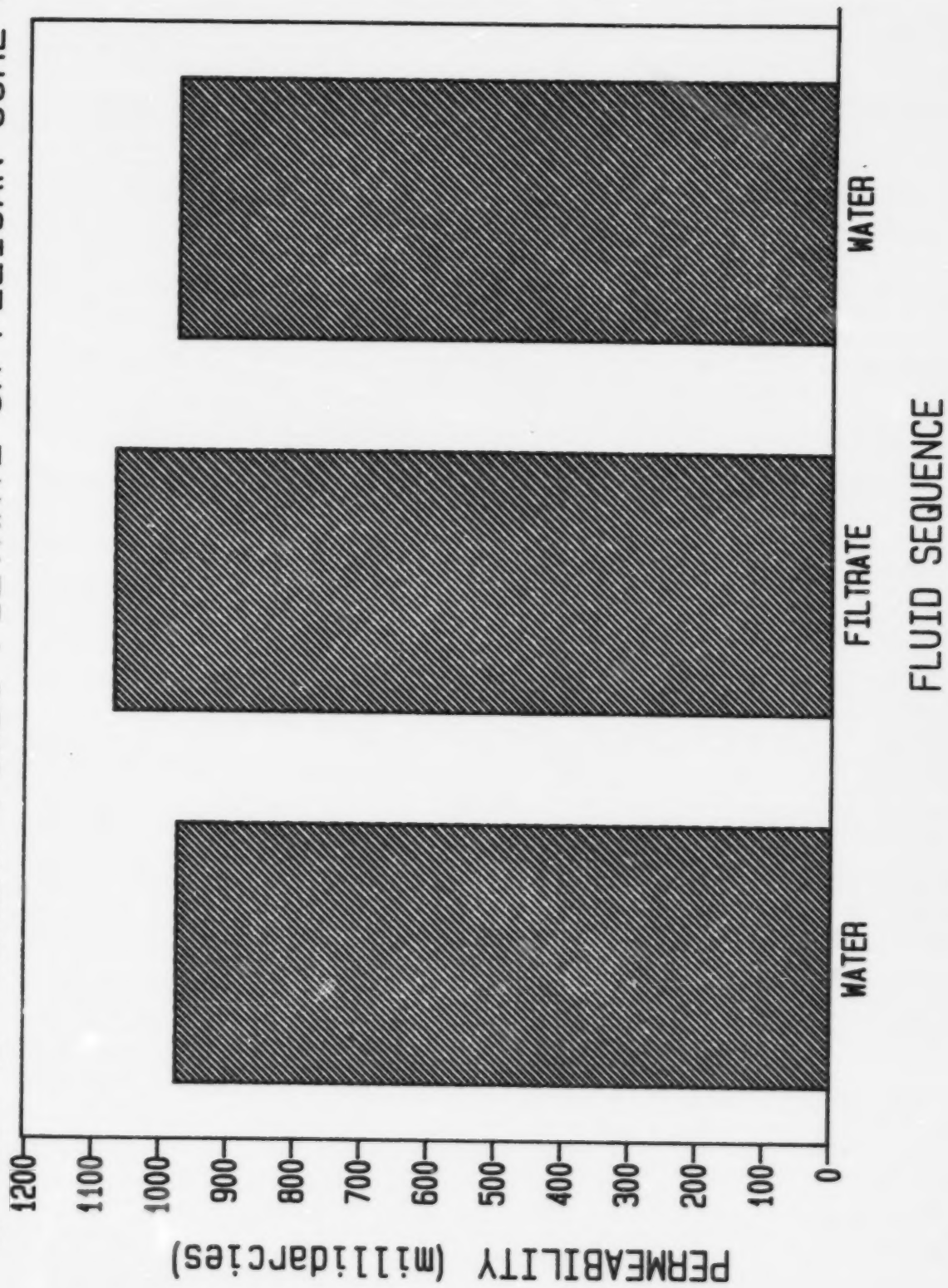


FIGURE 3B

DARCY REGIME FOR PELICAN CORE #6

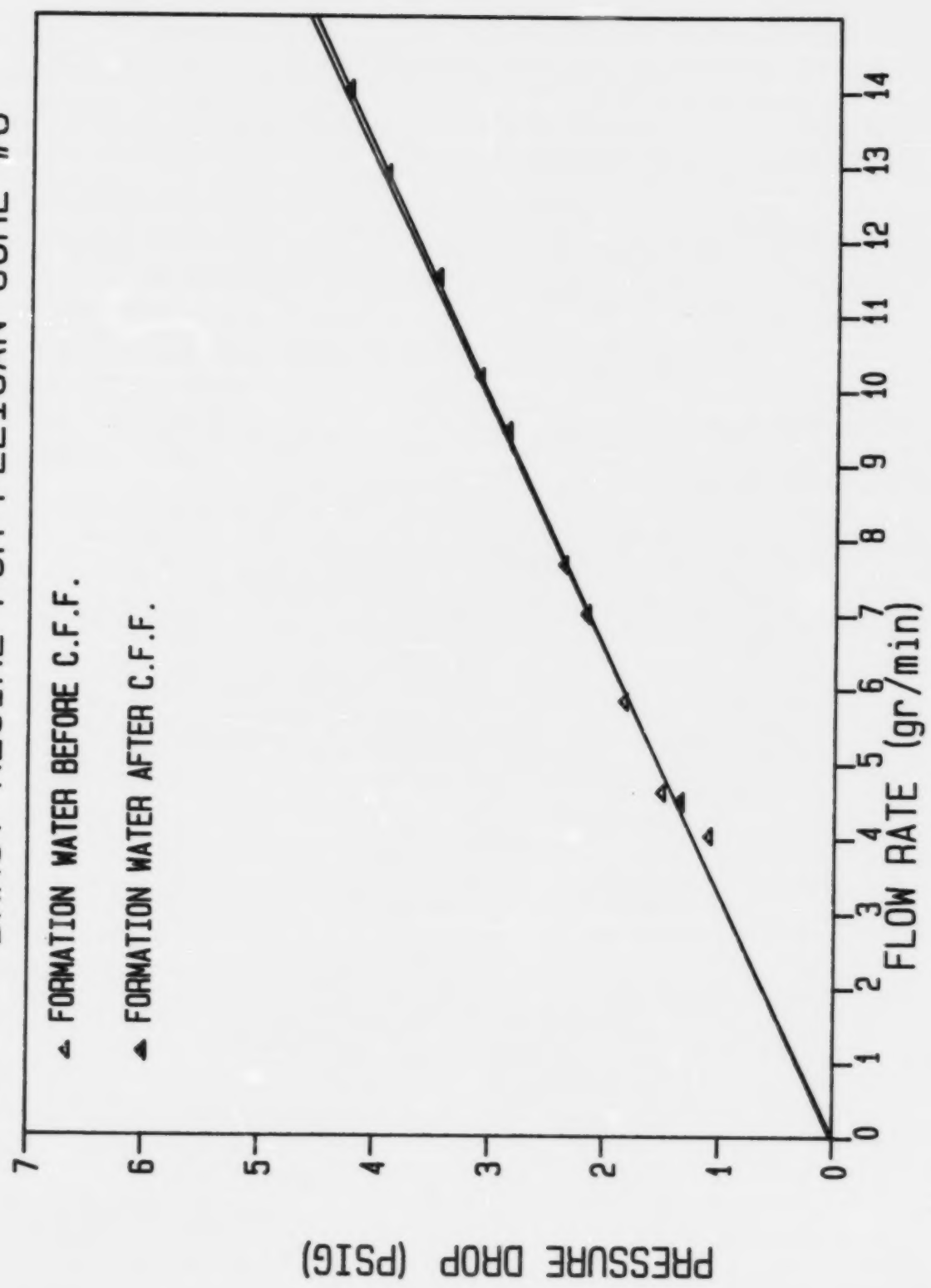


FIGURE 4A

EFFECT OF CLASS G CEMENT FILTRATE ON PELICAN #7

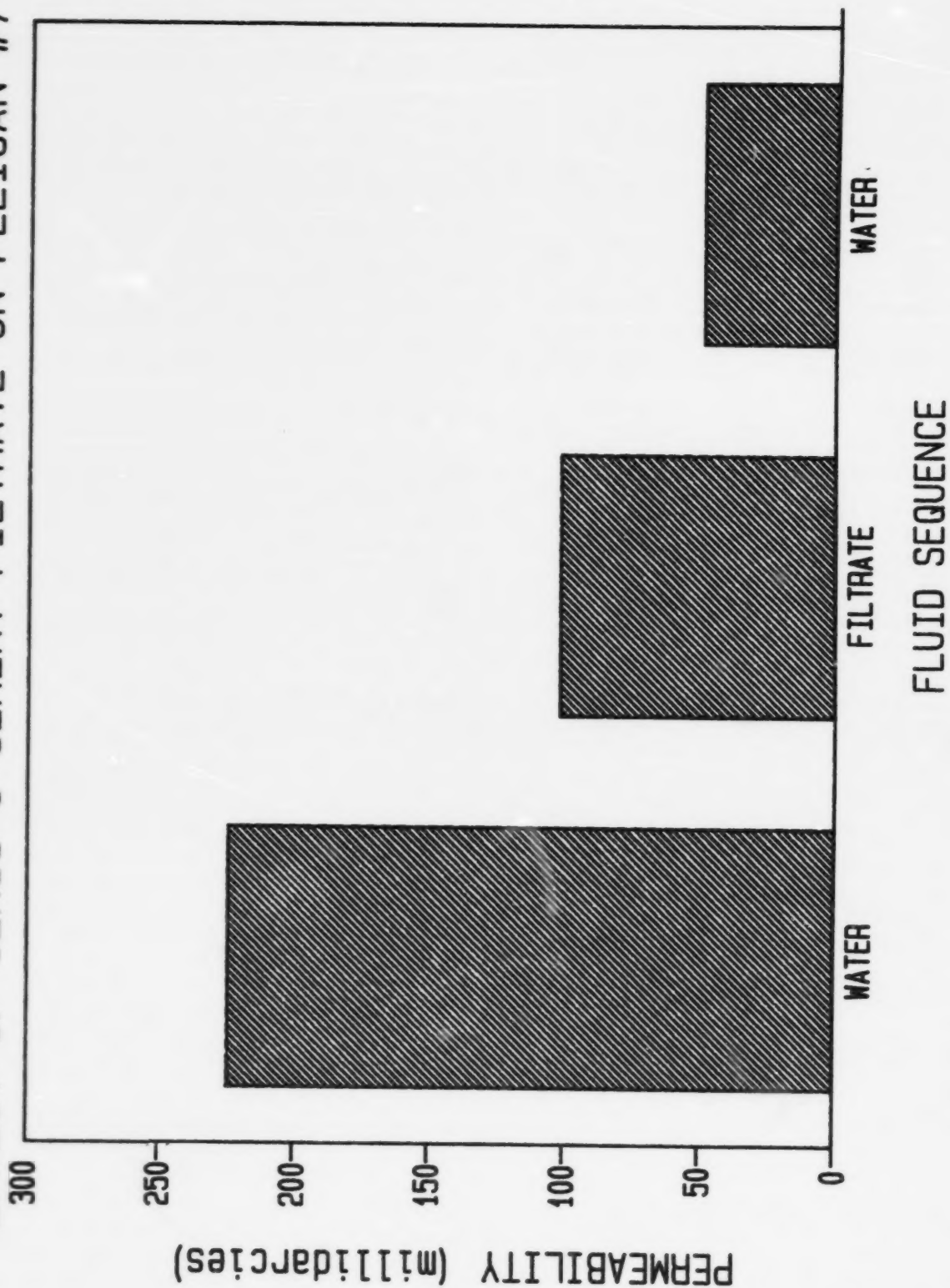


FIGURE 4B

DARCY REGIME FOR CORE #7

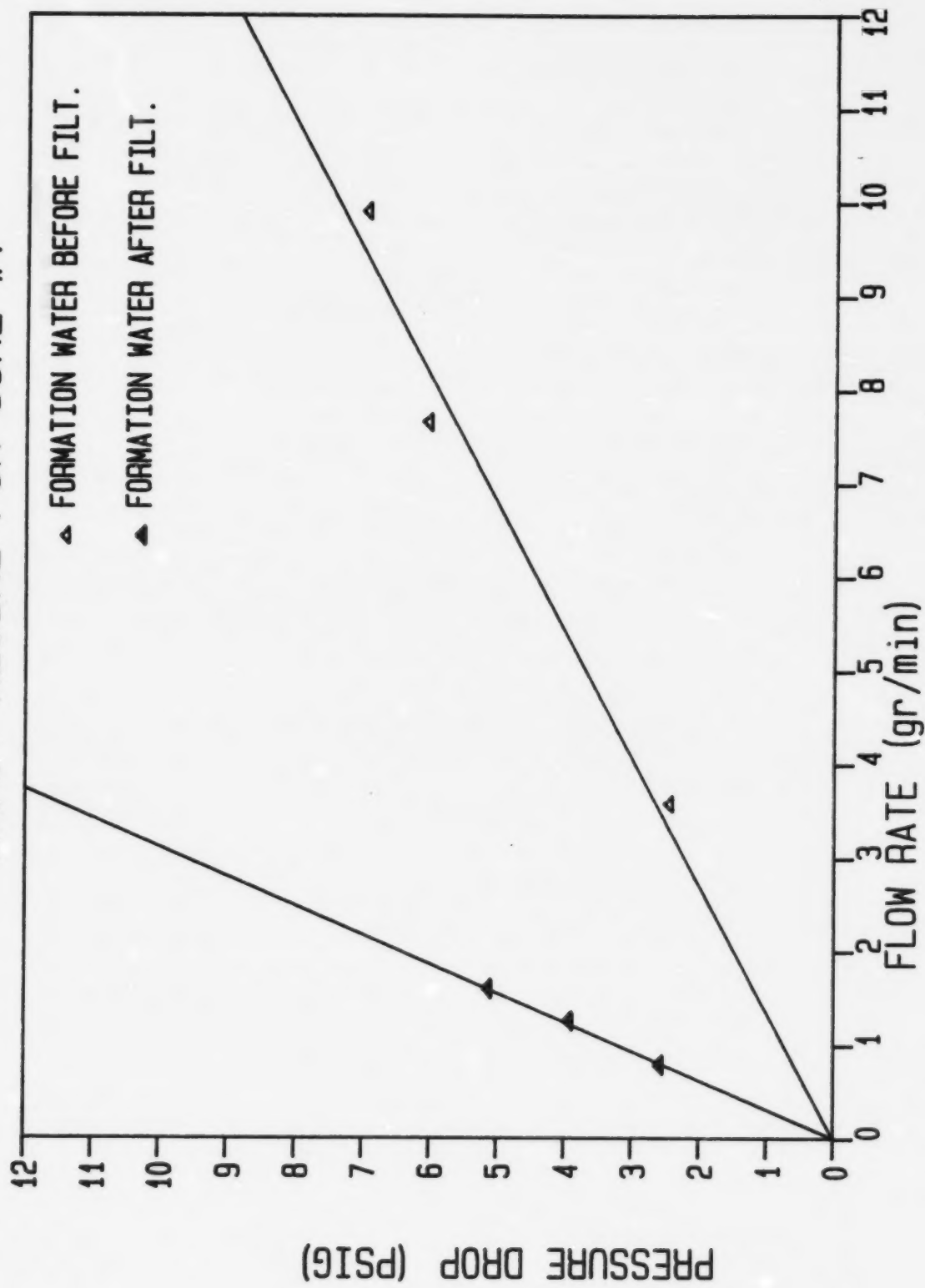


FIGURE 5A

EFFECT OF CLASS G CEMENT FILTRATE ON EDAM CORE 2

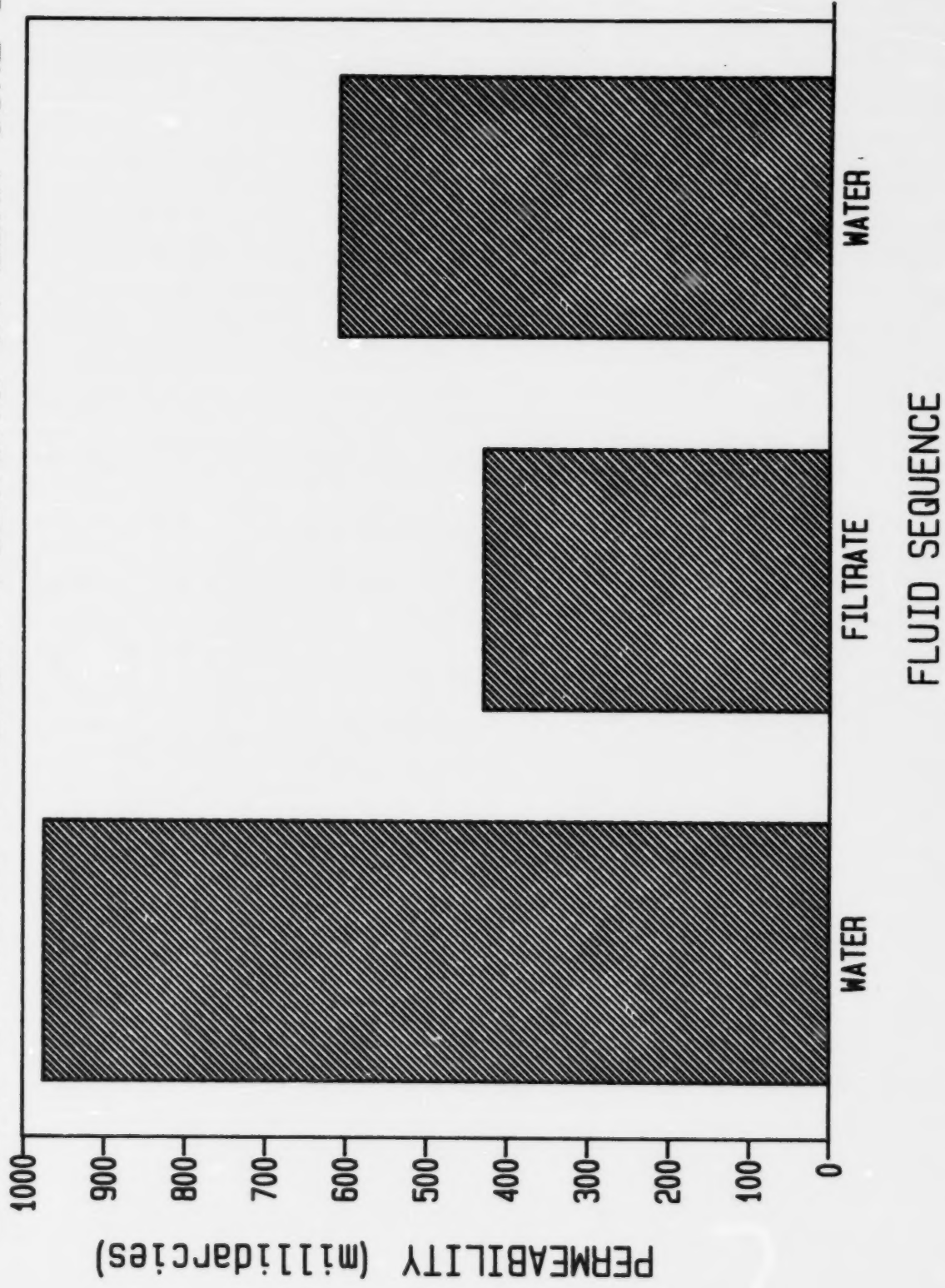


FIGURE 5B

DARCY REGIME FOR EDAM CORE 2

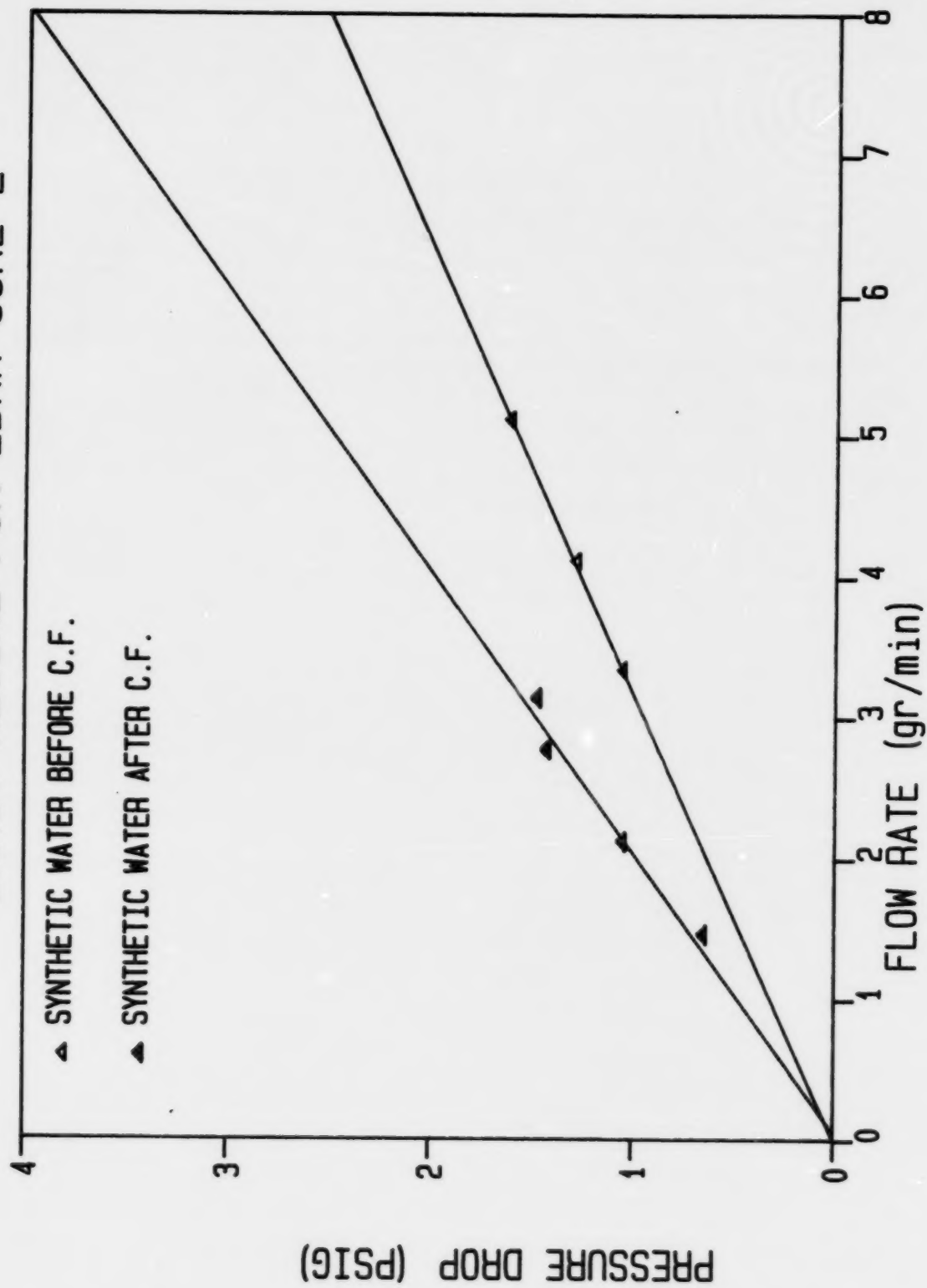


FIGURE 6A

EFFECT OF CEMENT FONDU FILTRATE ON EDAM CORE 3

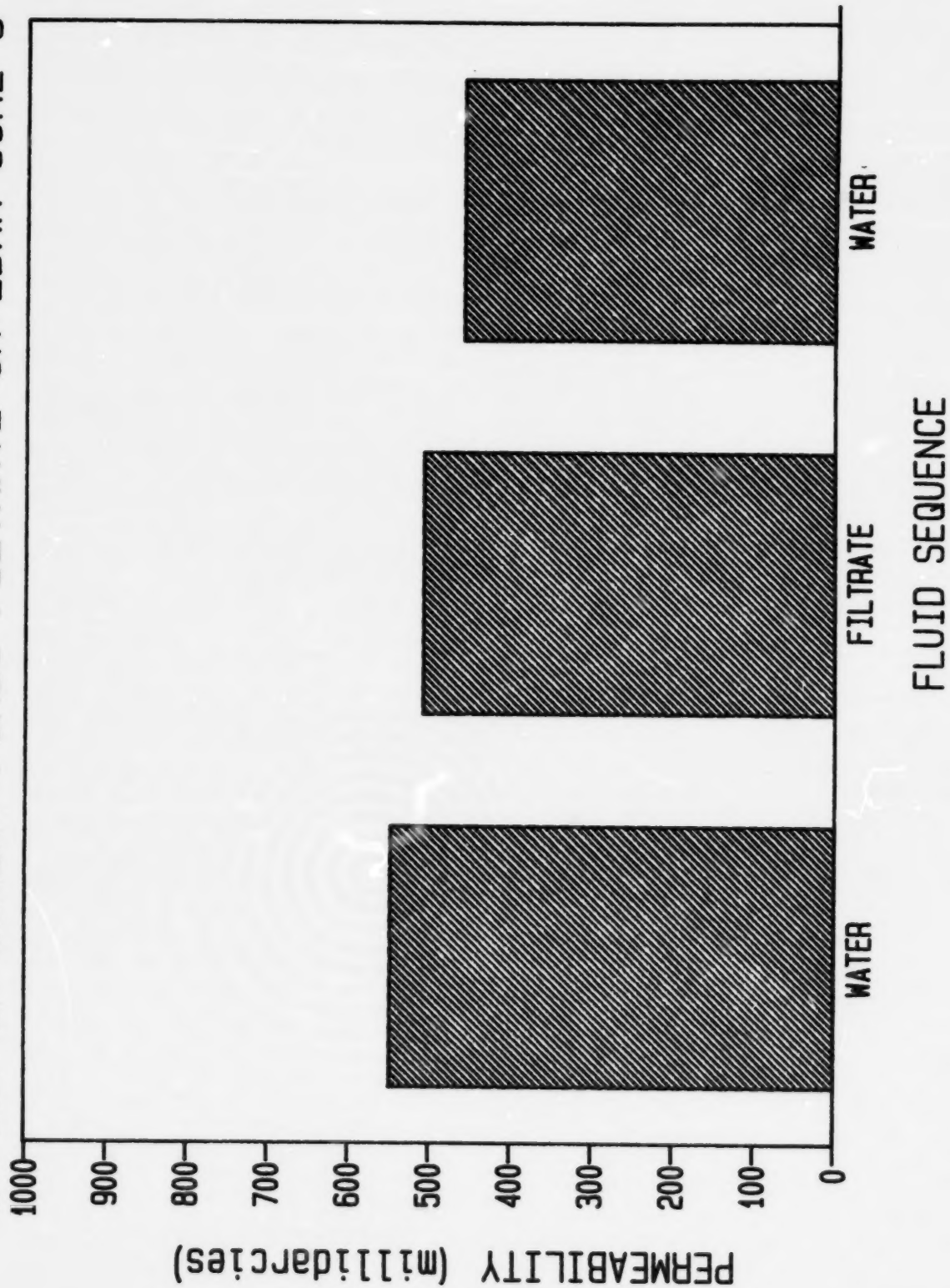


FIGURE 6B

DARCY REGIME FOR EDAM CORE 3

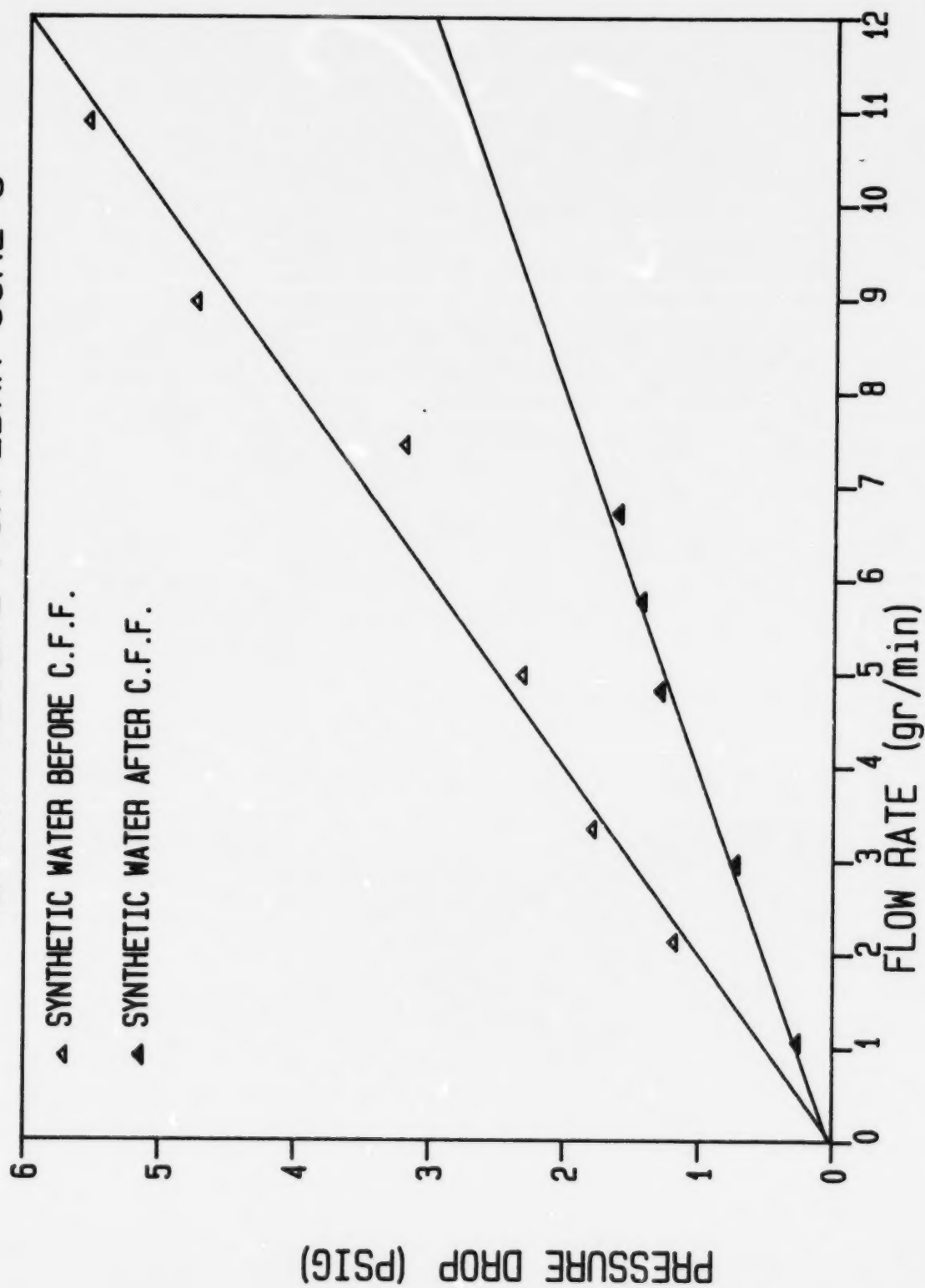


FIGURE 7A

EFFECT OF CLASS G CEMENT FILTRATE ON EDAM CORE 4

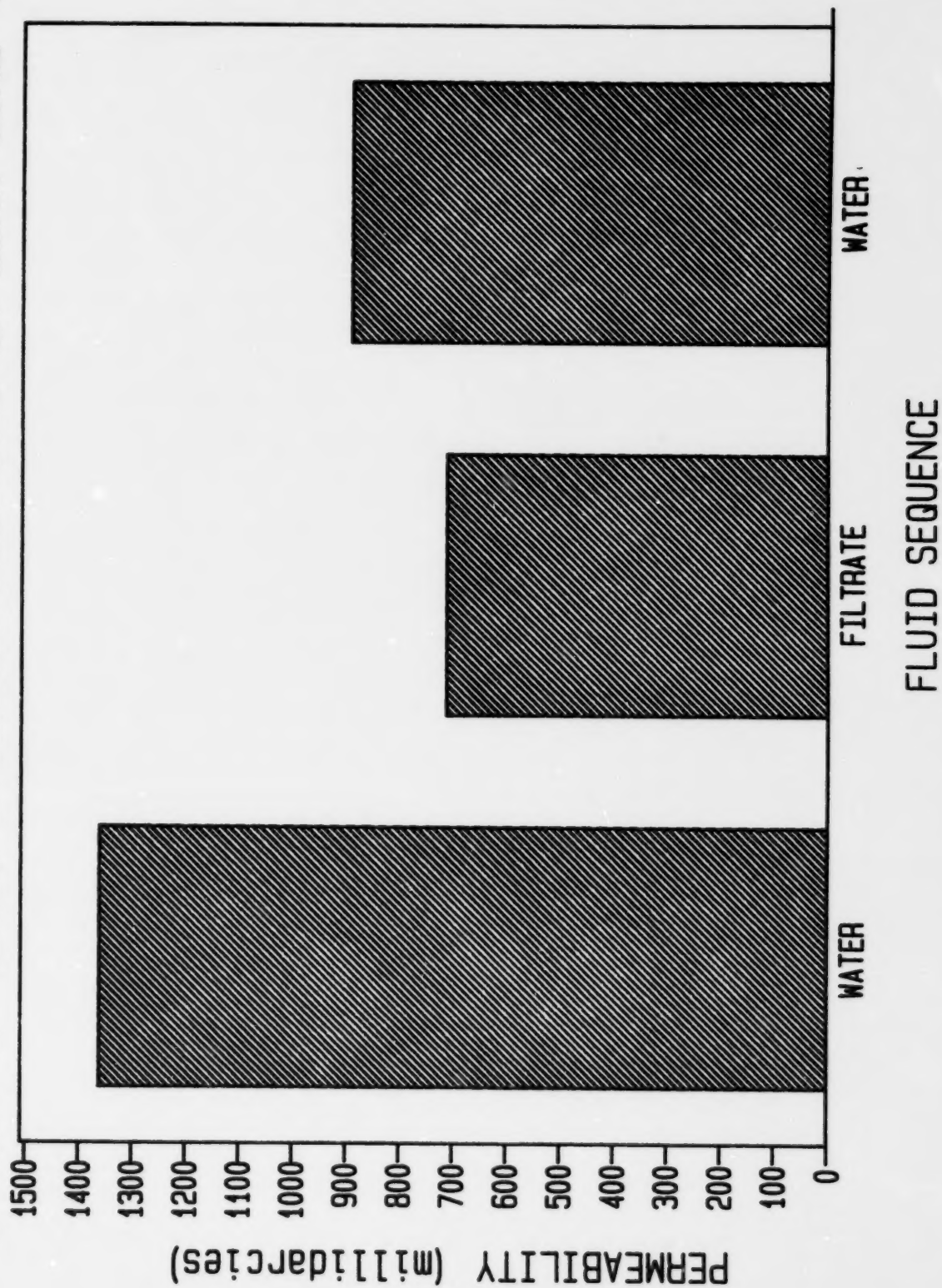


FIGURE 7B

DARCY REGIME FOR EDAM CORE 4

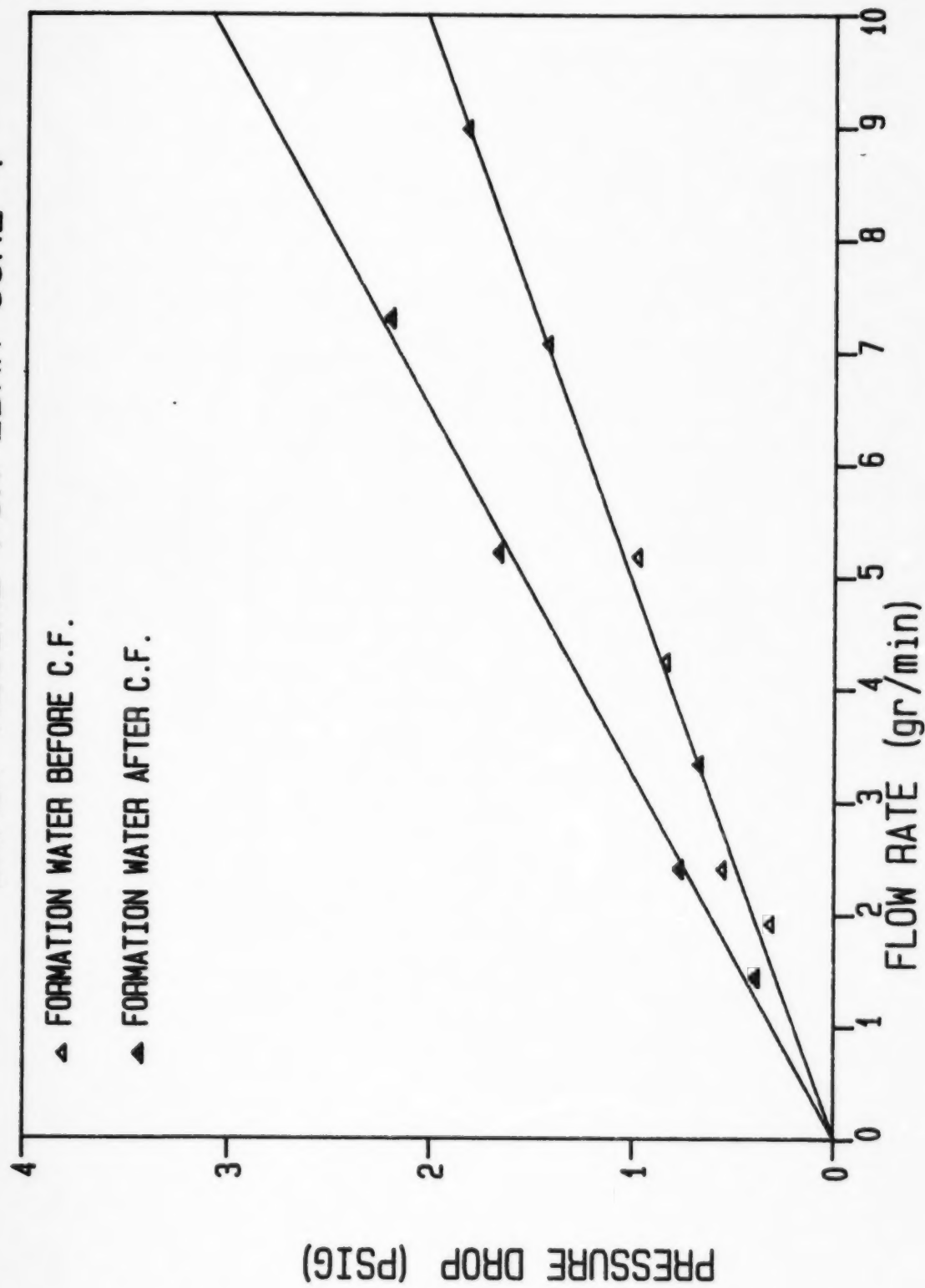


FIGURE 8A

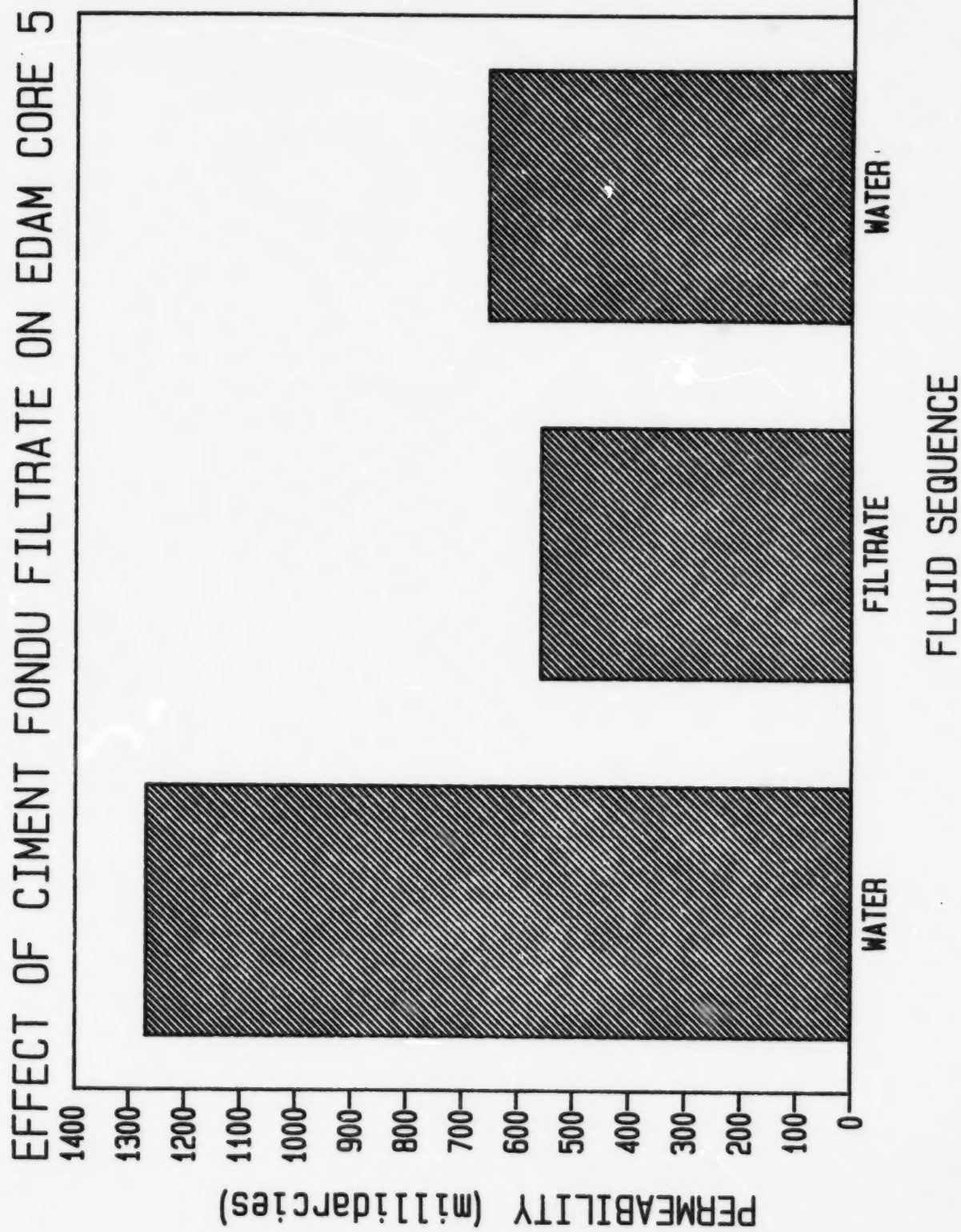


FIGURE 8B

DARCY REGIME FOR EDAM CORE 5

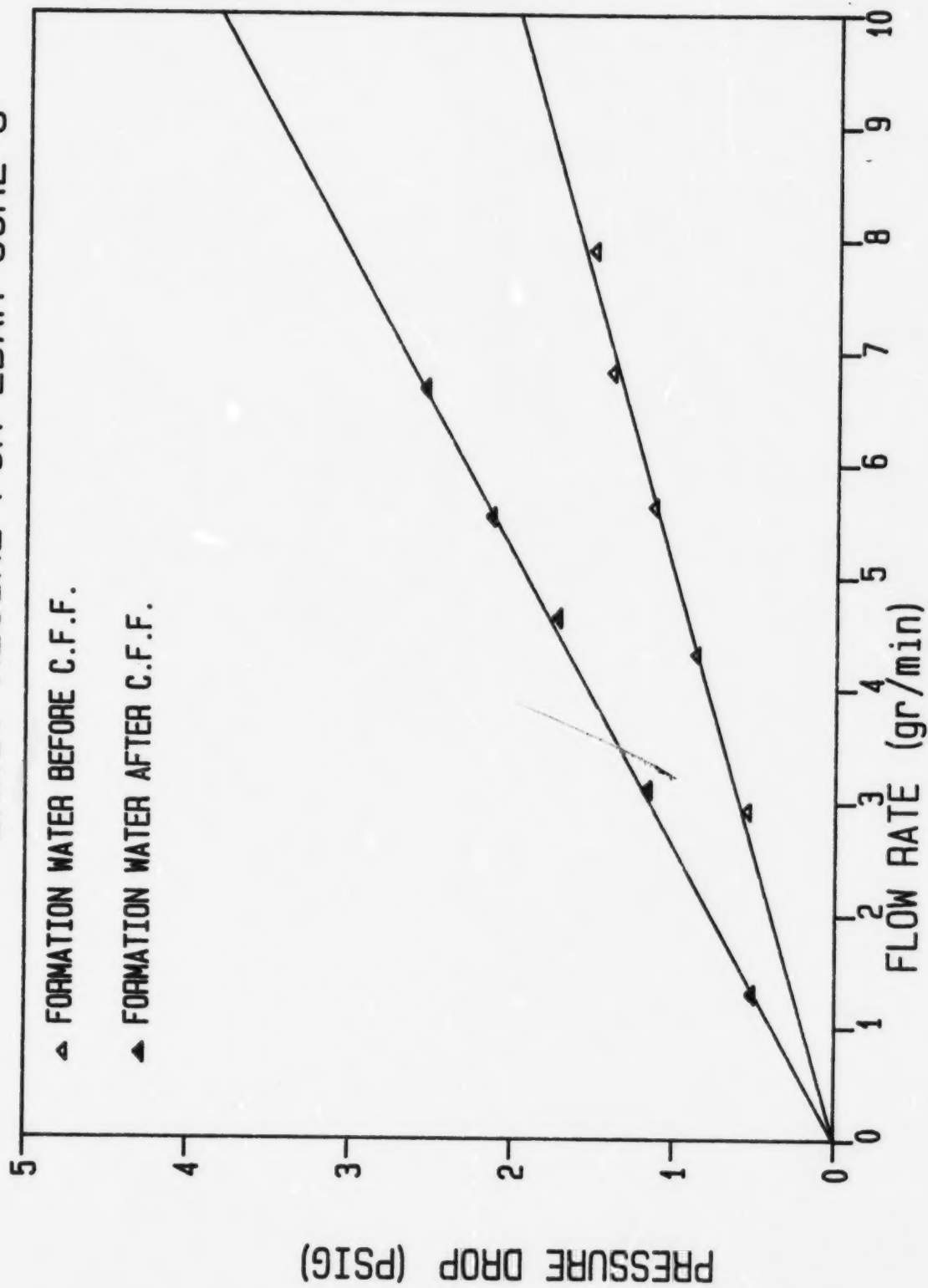


FIGURE 9A

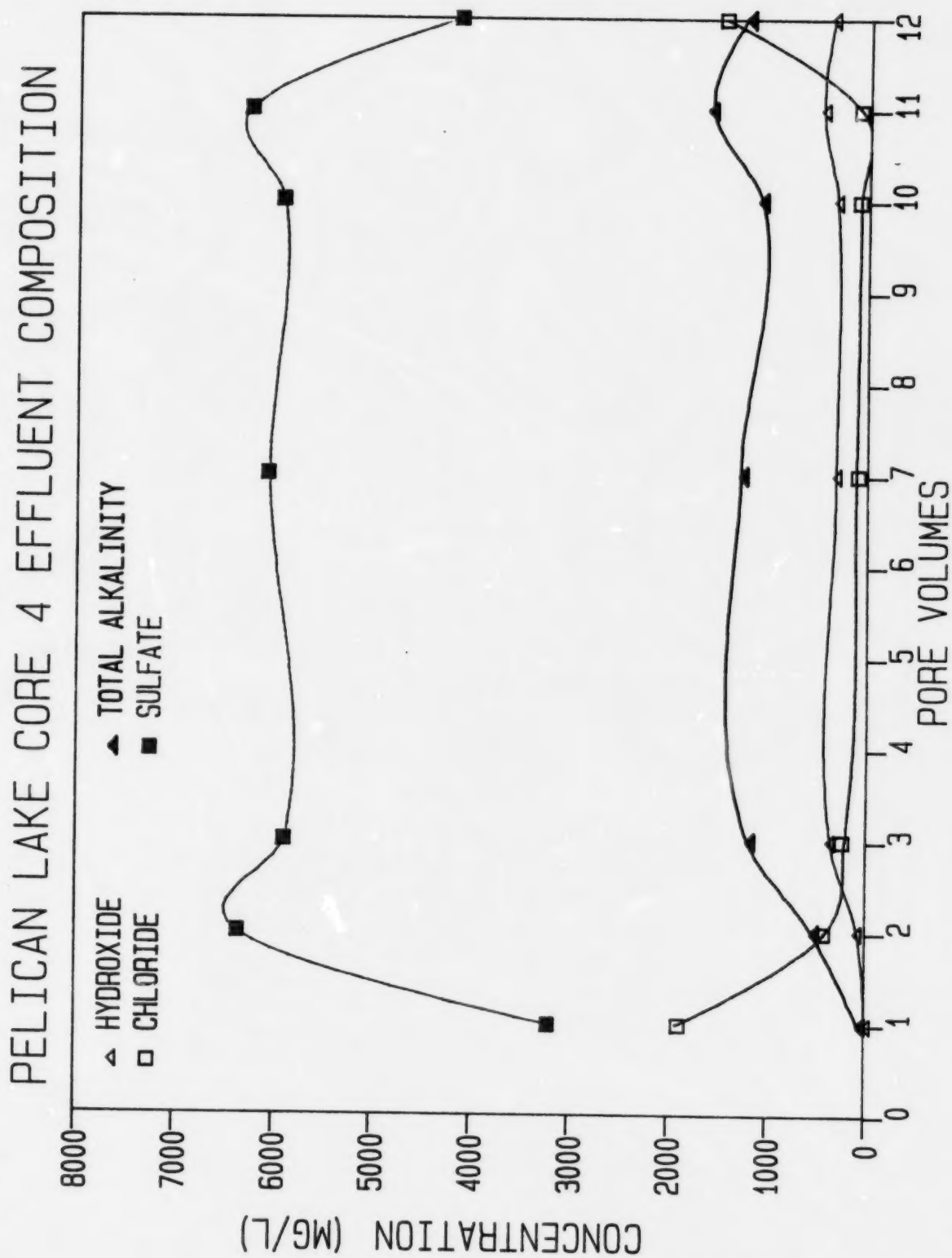


FIGURE 9B
 PELICAN LAKE CORE 4 EFFLUENT COMPOSITION

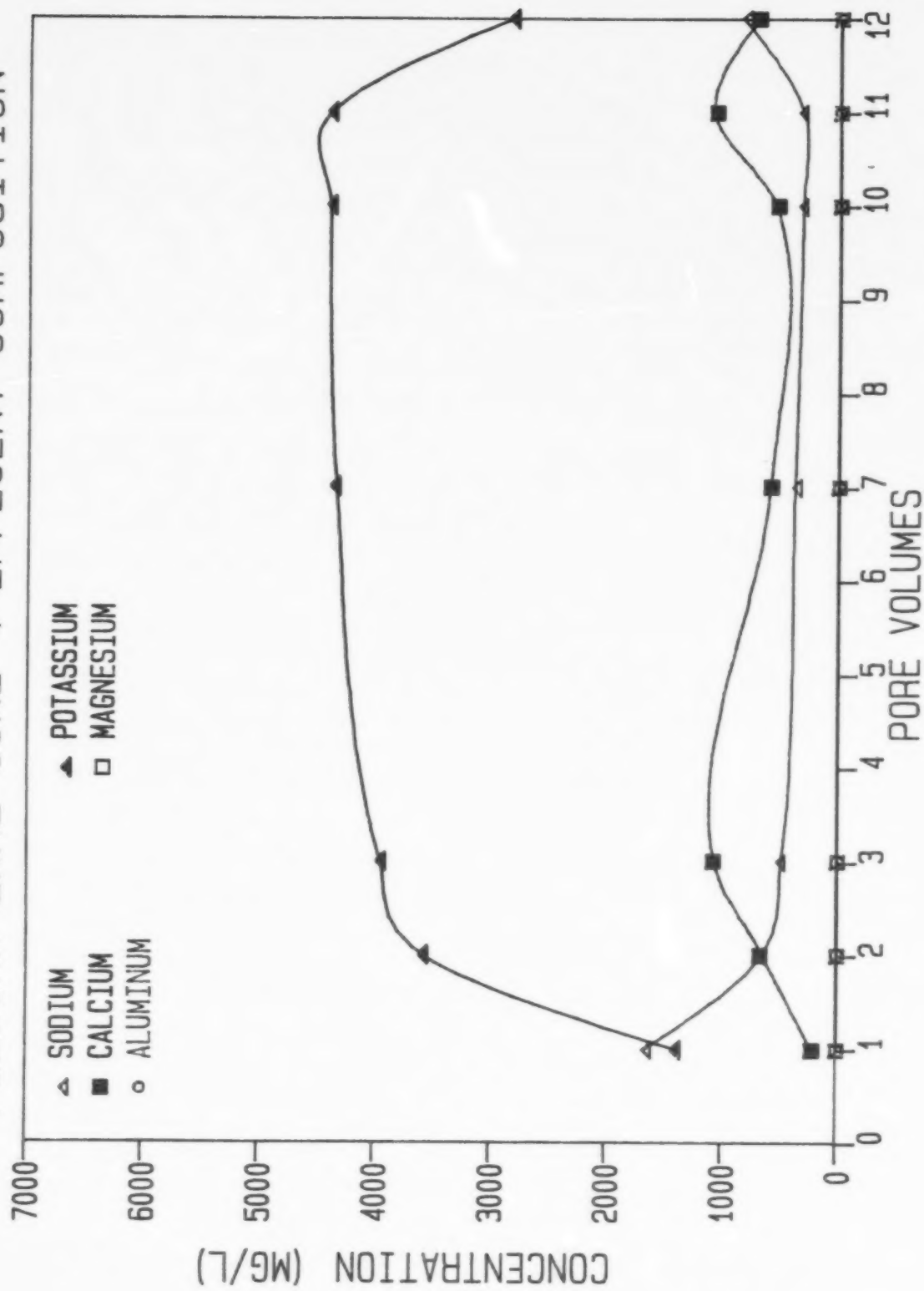


FIGURE 10A

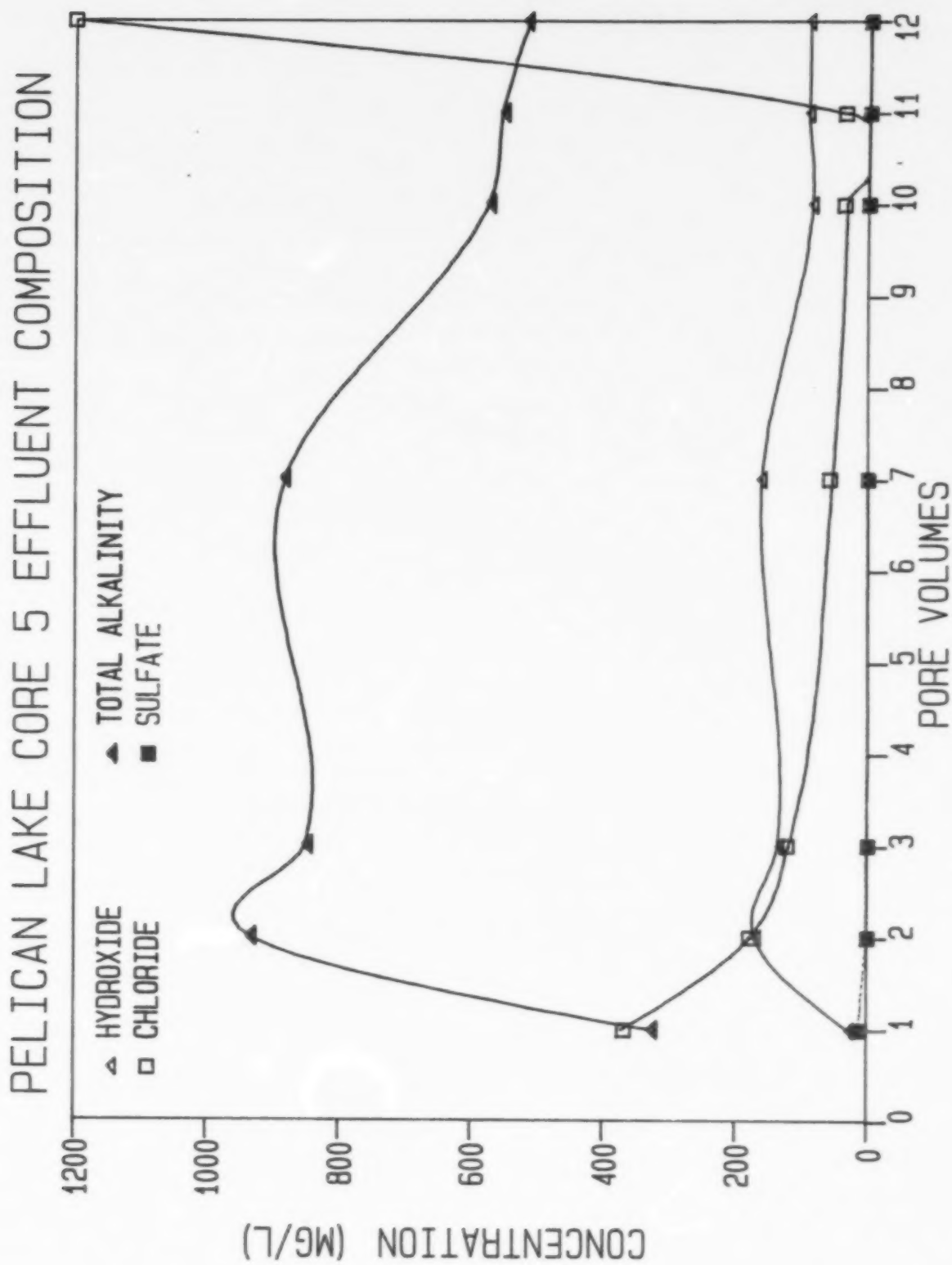


FIGURE 10B

PELICAN LAKE CORE 5 EFFLUENT COMPOSITION

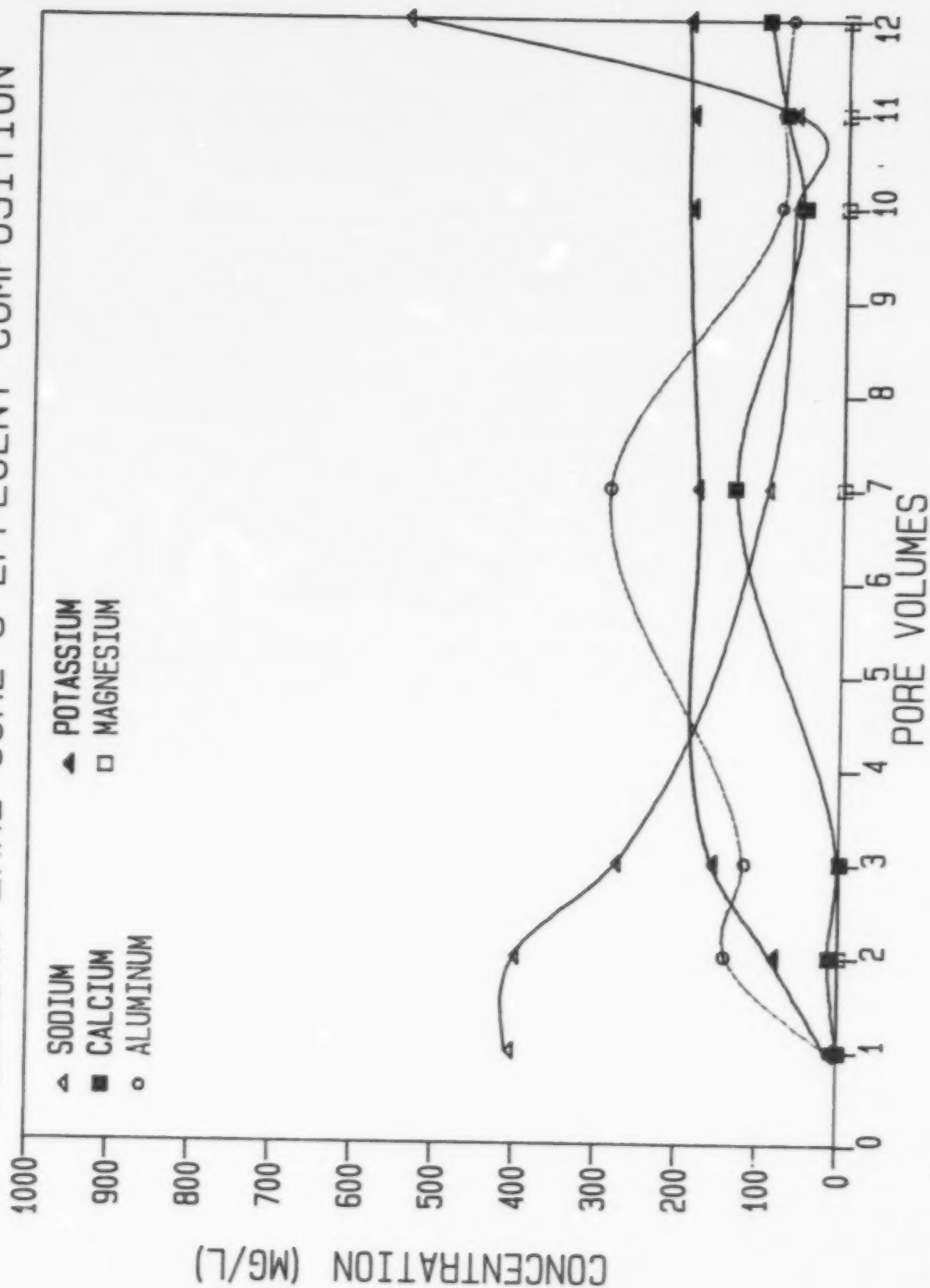


FIGURE 11 A
PELICAN LAKE CORE 6 EFFLUENT COMPOSITION

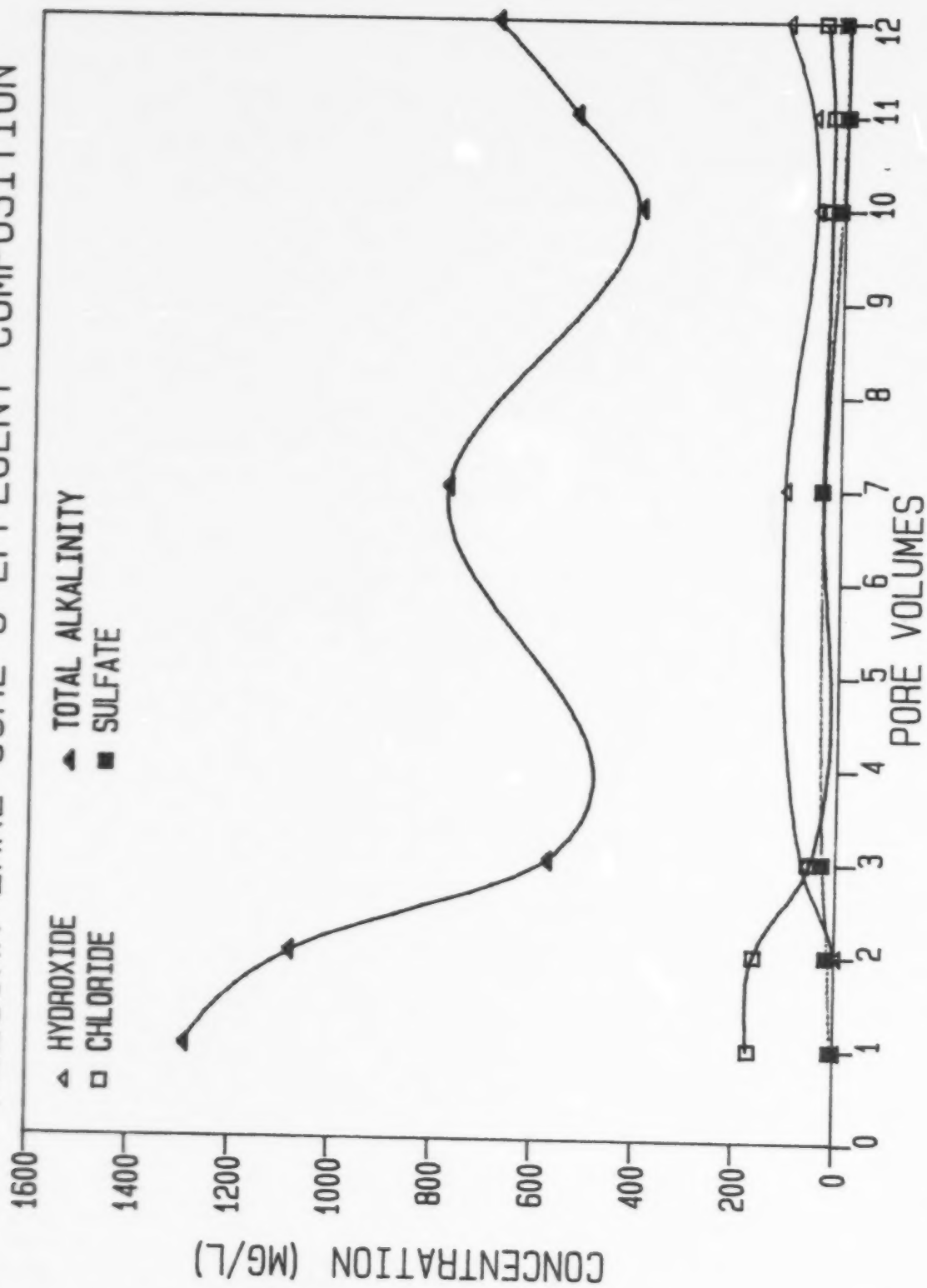


FIGURE 11B

PELICAN LAKE CORE 6 EFFLUENT COMPOSITION

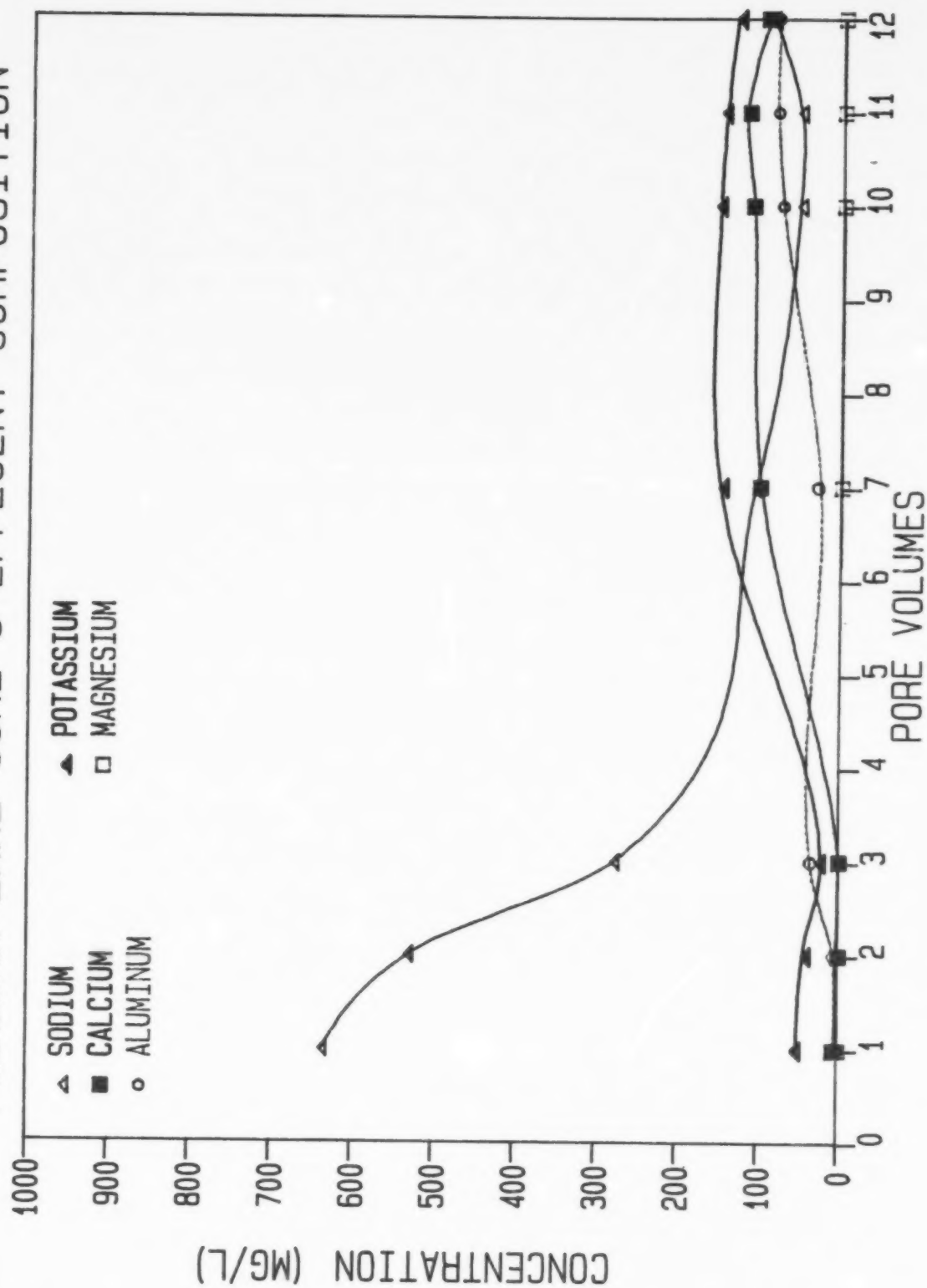


FIGURE 12 A

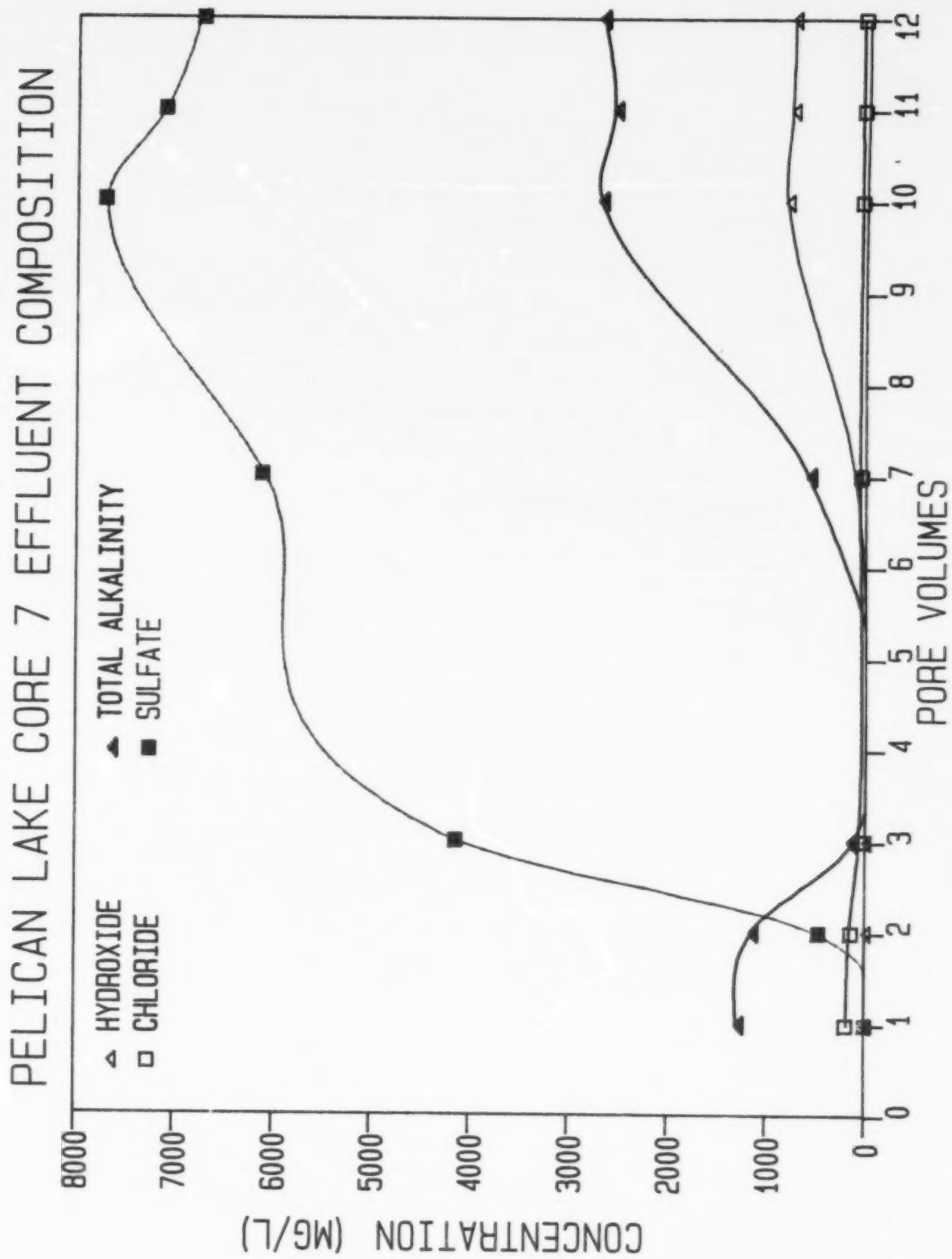


FIGURE 12B

PELICAN LAKE CORE 7 EFFLUENT COMPOSITION

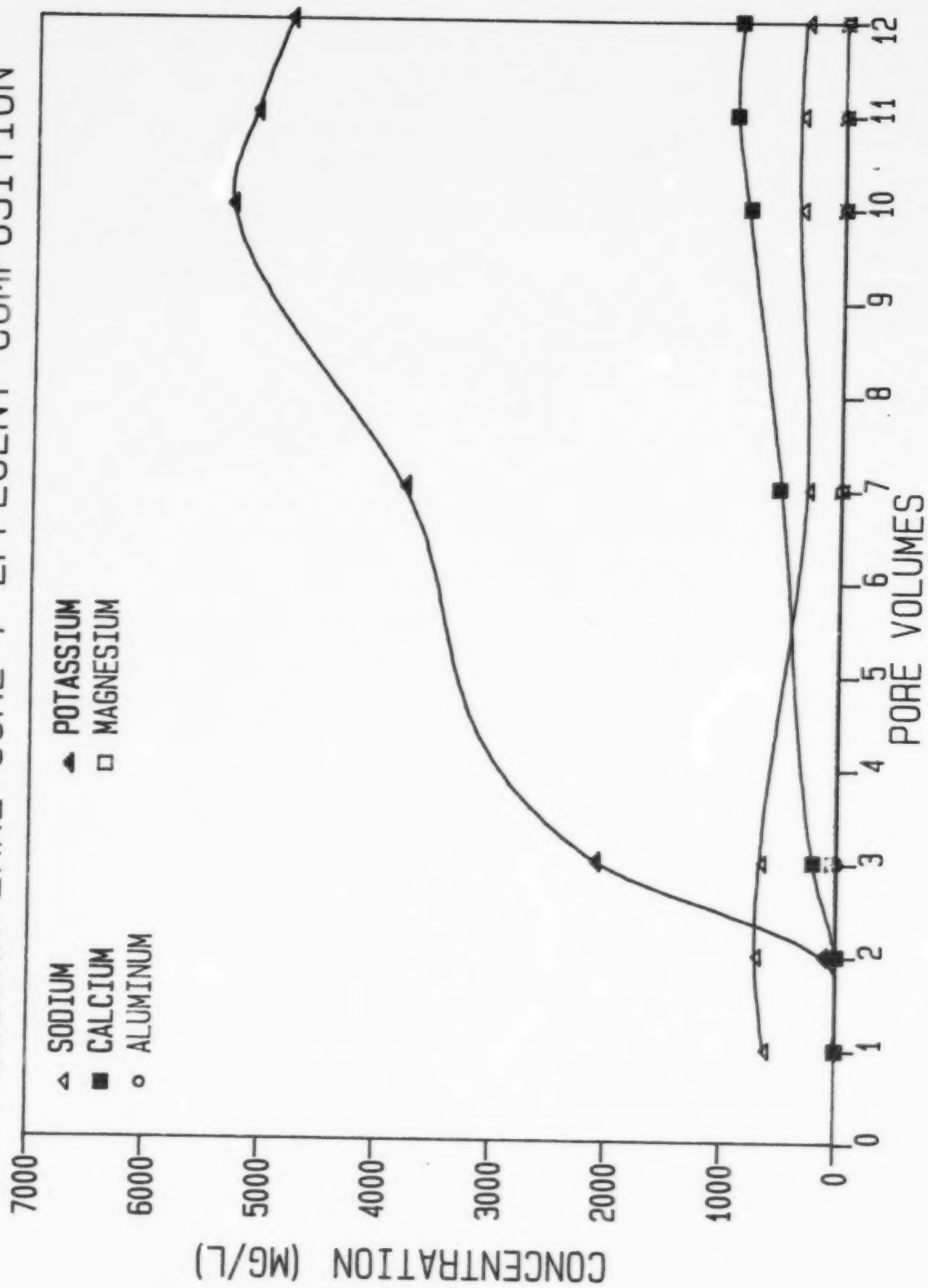


FIGURE 13 A

WEST EDAM CORE 2 EFFLUENT COMPOSITION

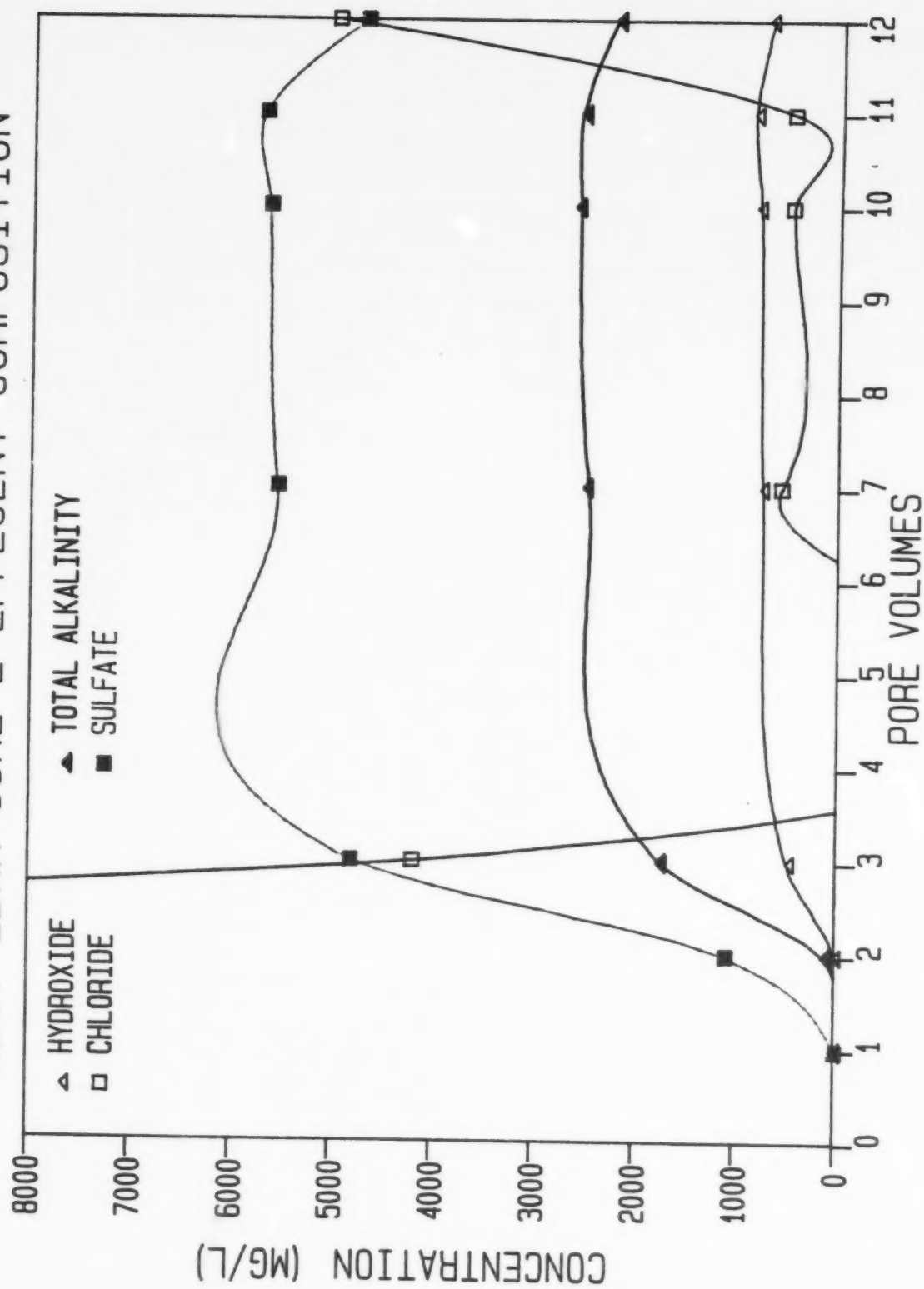


FIGURE 13B
WEST EDAM CORE 2 EFFLUENT COMPOSITION

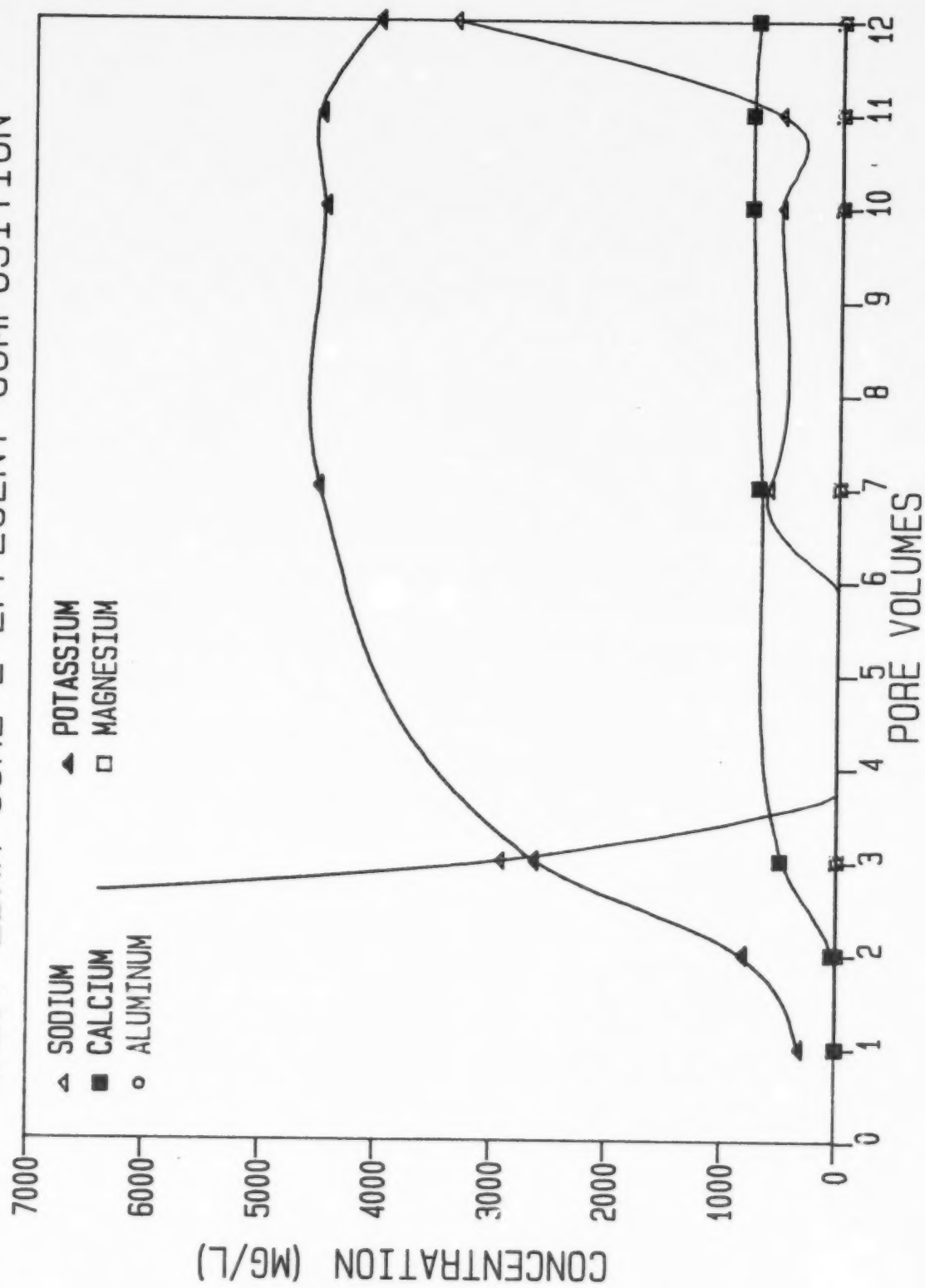


FIGURE 14 A

WEST EDAM CORE 4 EFFLUENT COMPOSITION

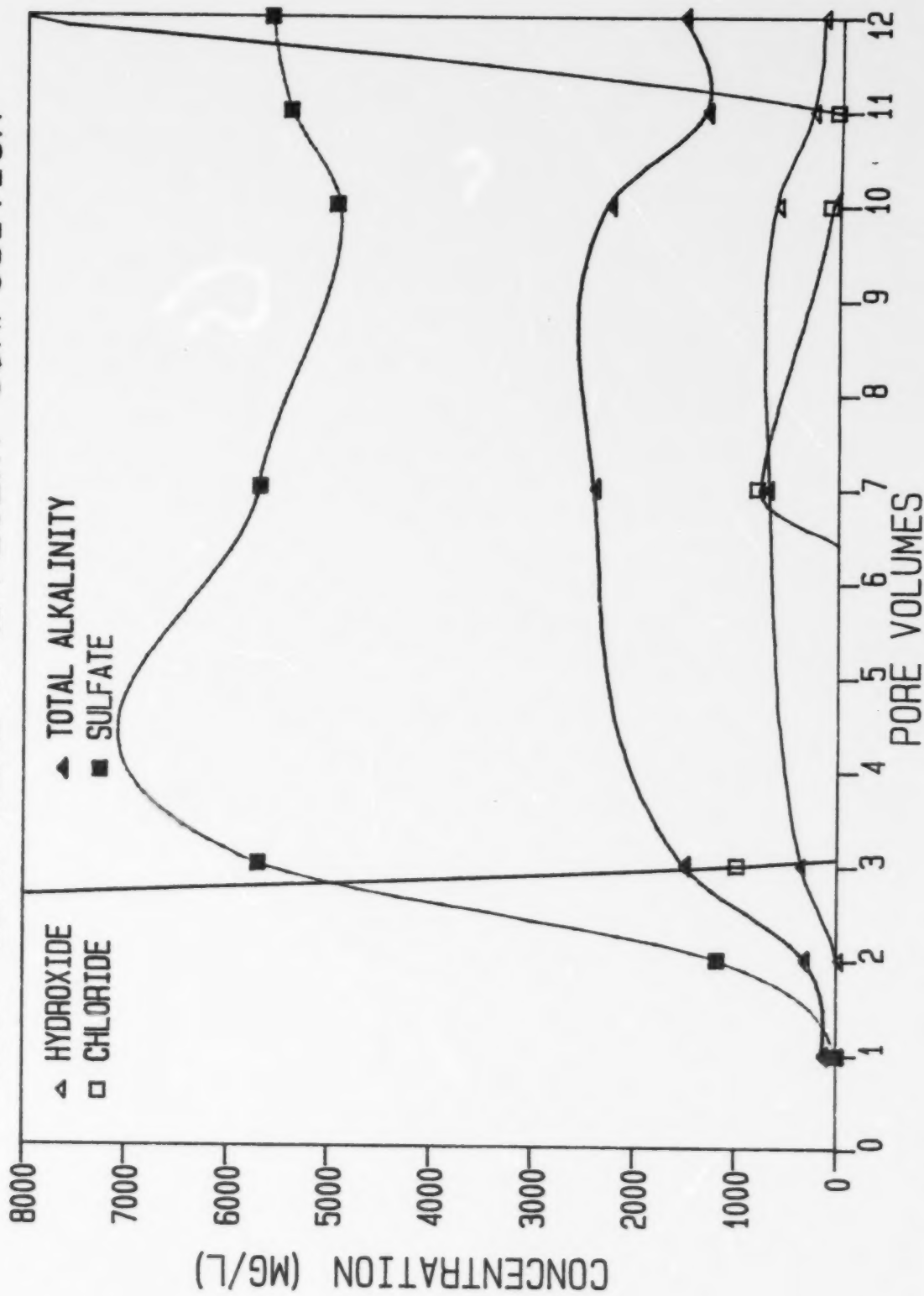


FIGURE 14B

WEST EDAM CORE 4 EFFLUENT COMPOSITION

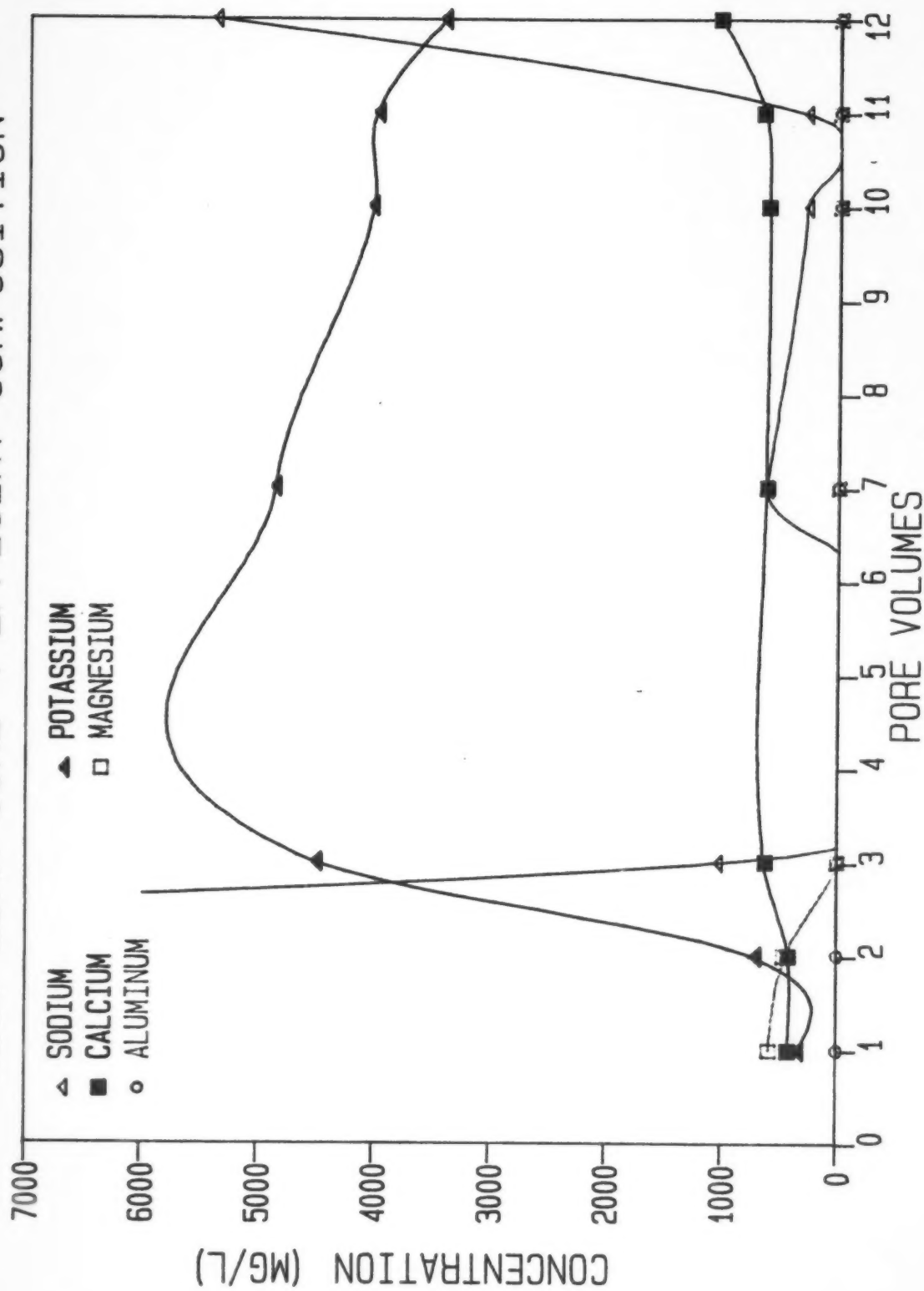


FIGURE 15

pH OF CORE EFFLUENTS

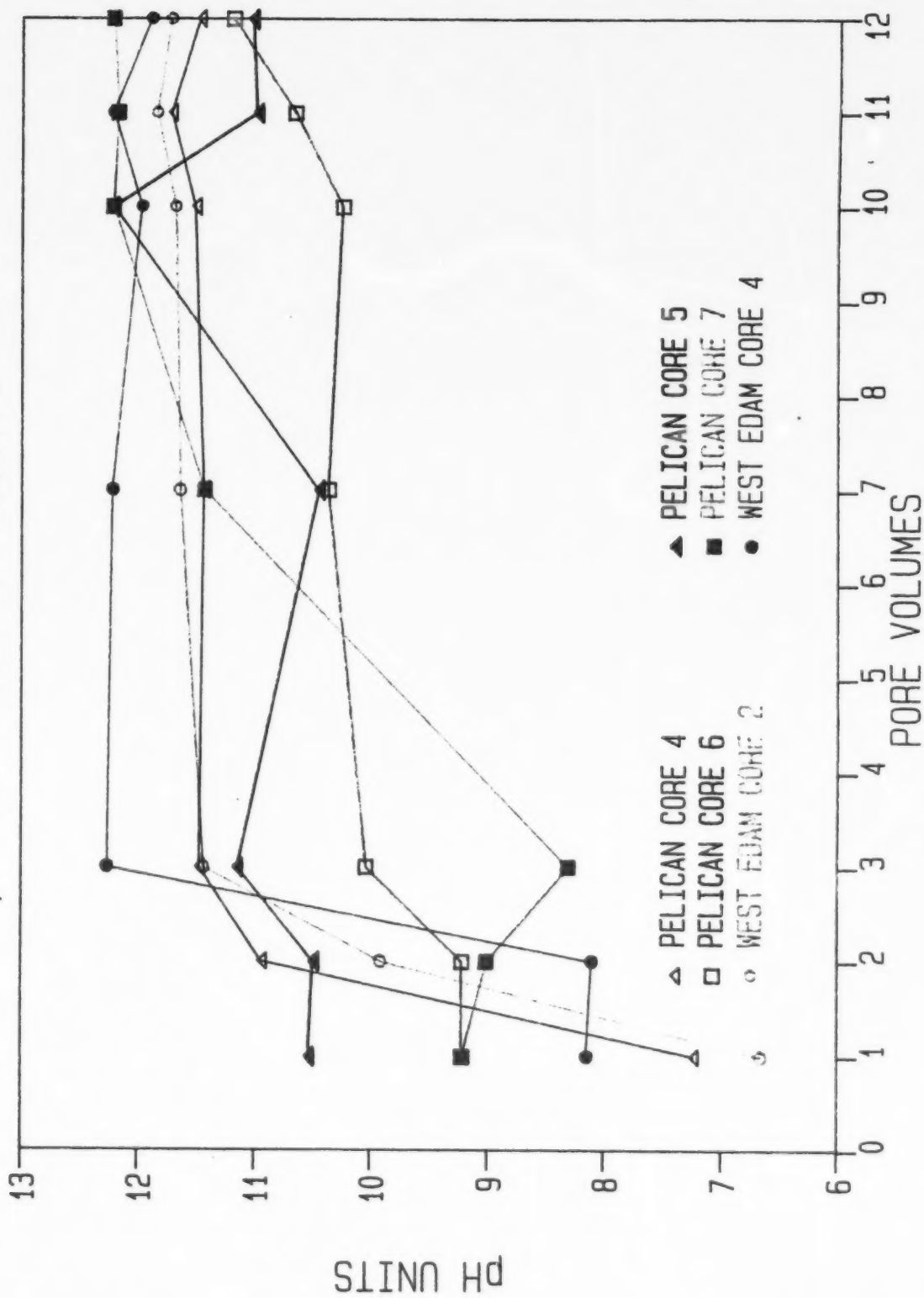


FIGURE 16

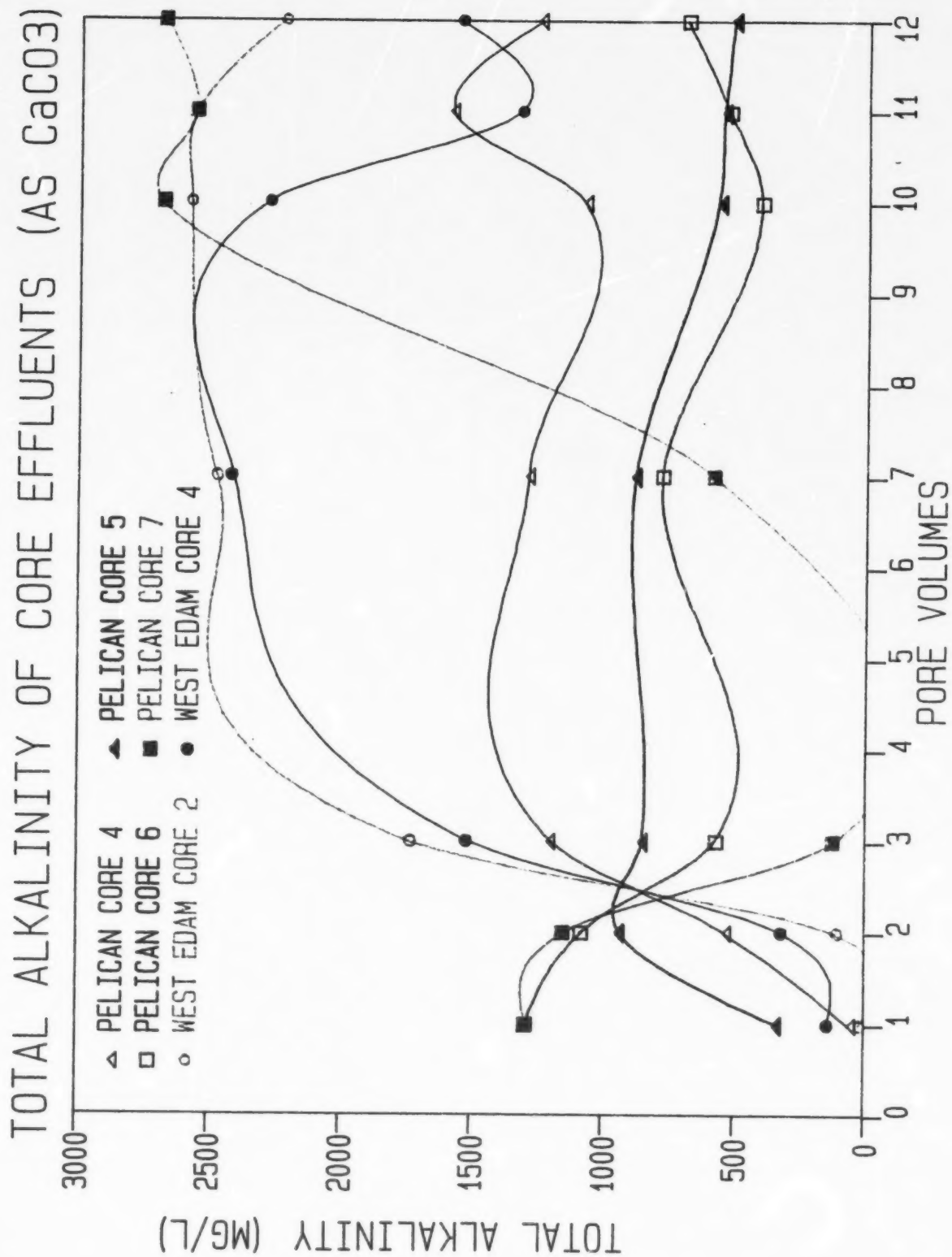


FIGURE 17

HYDROXIDE IN CORE EFFLUENTS

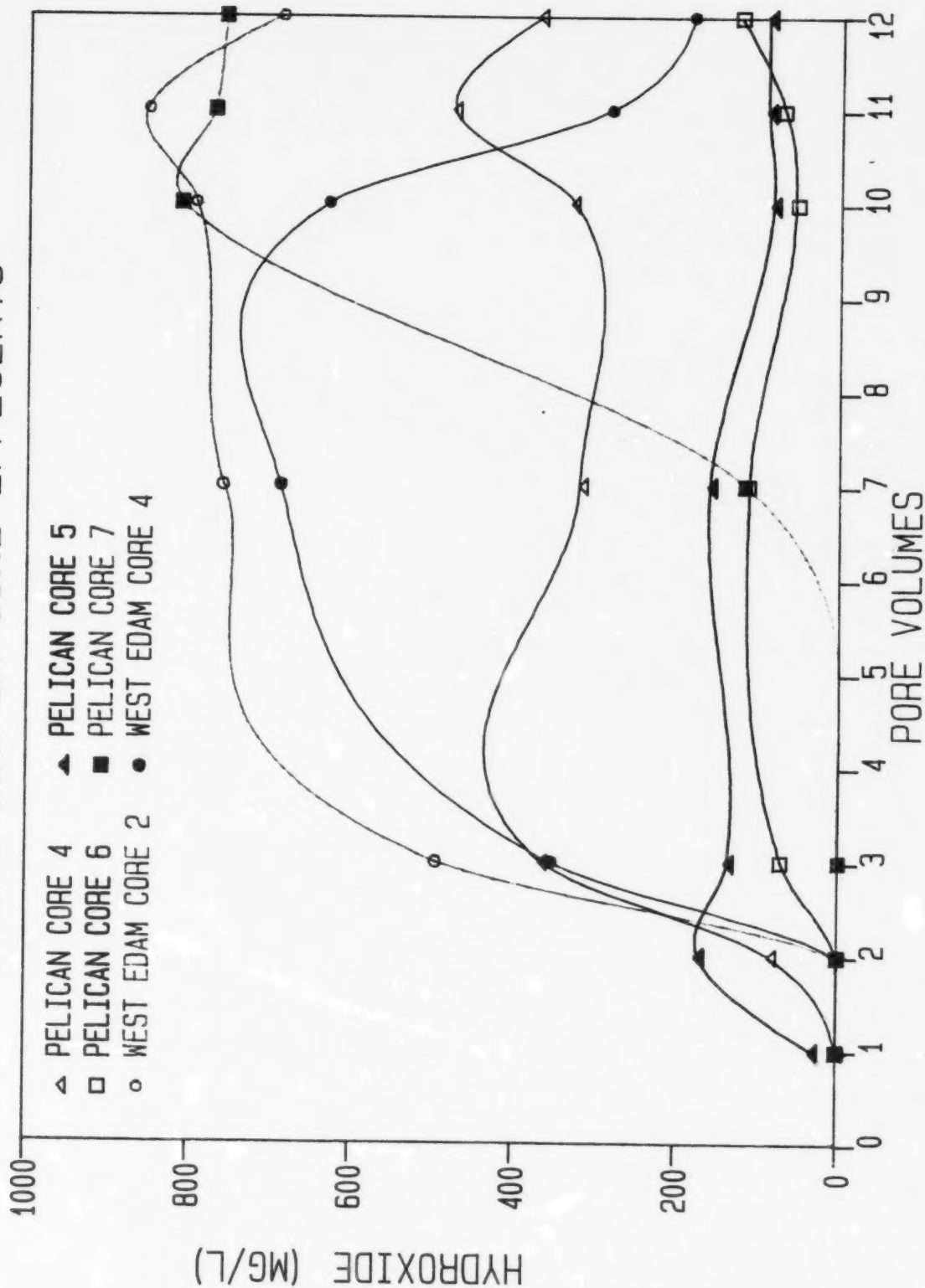


FIGURE 18

SULFATE IN CORE EFFLUENTS

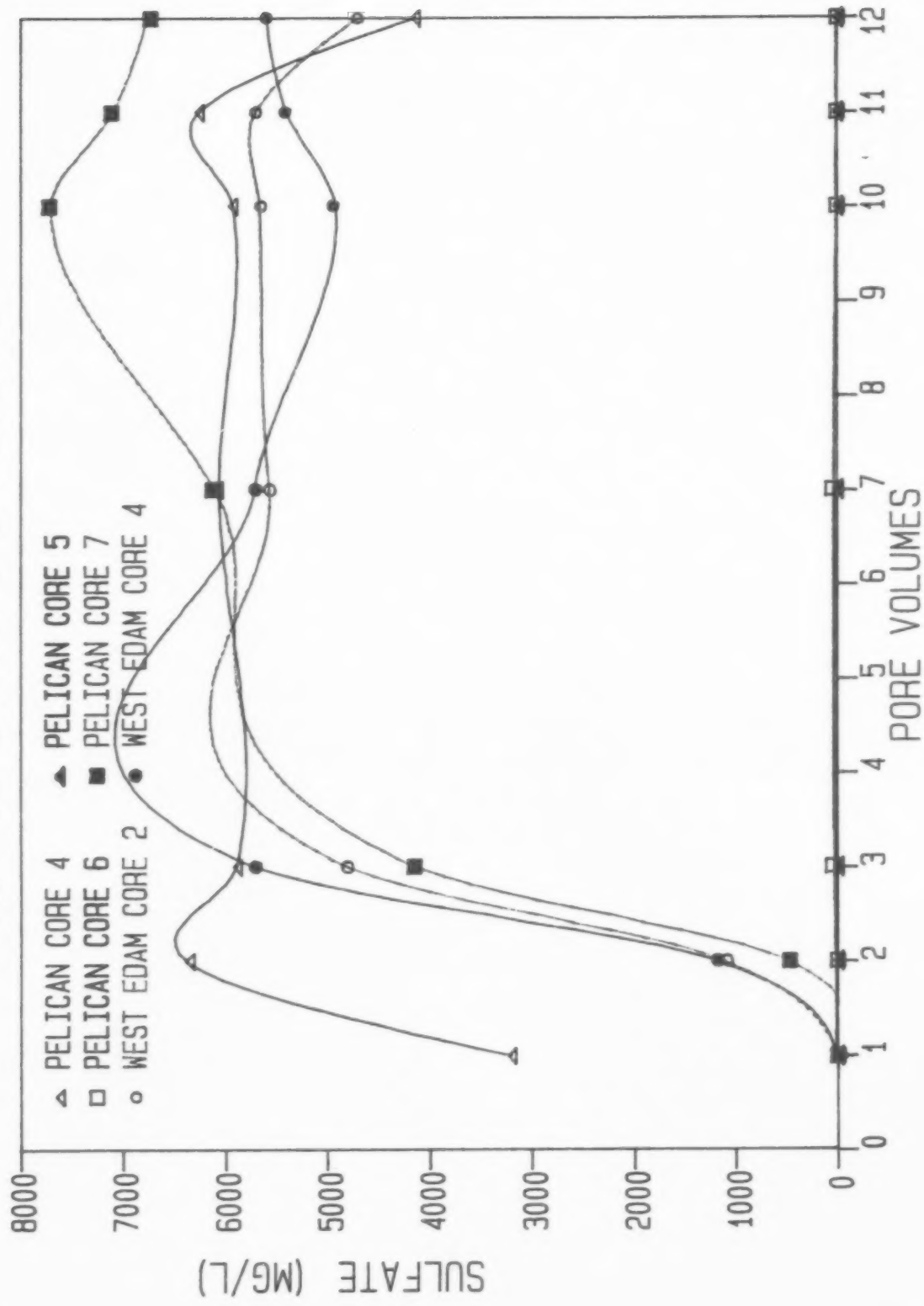


FIGURE 19

CHLORIDE IN CORE EFFLUENTS

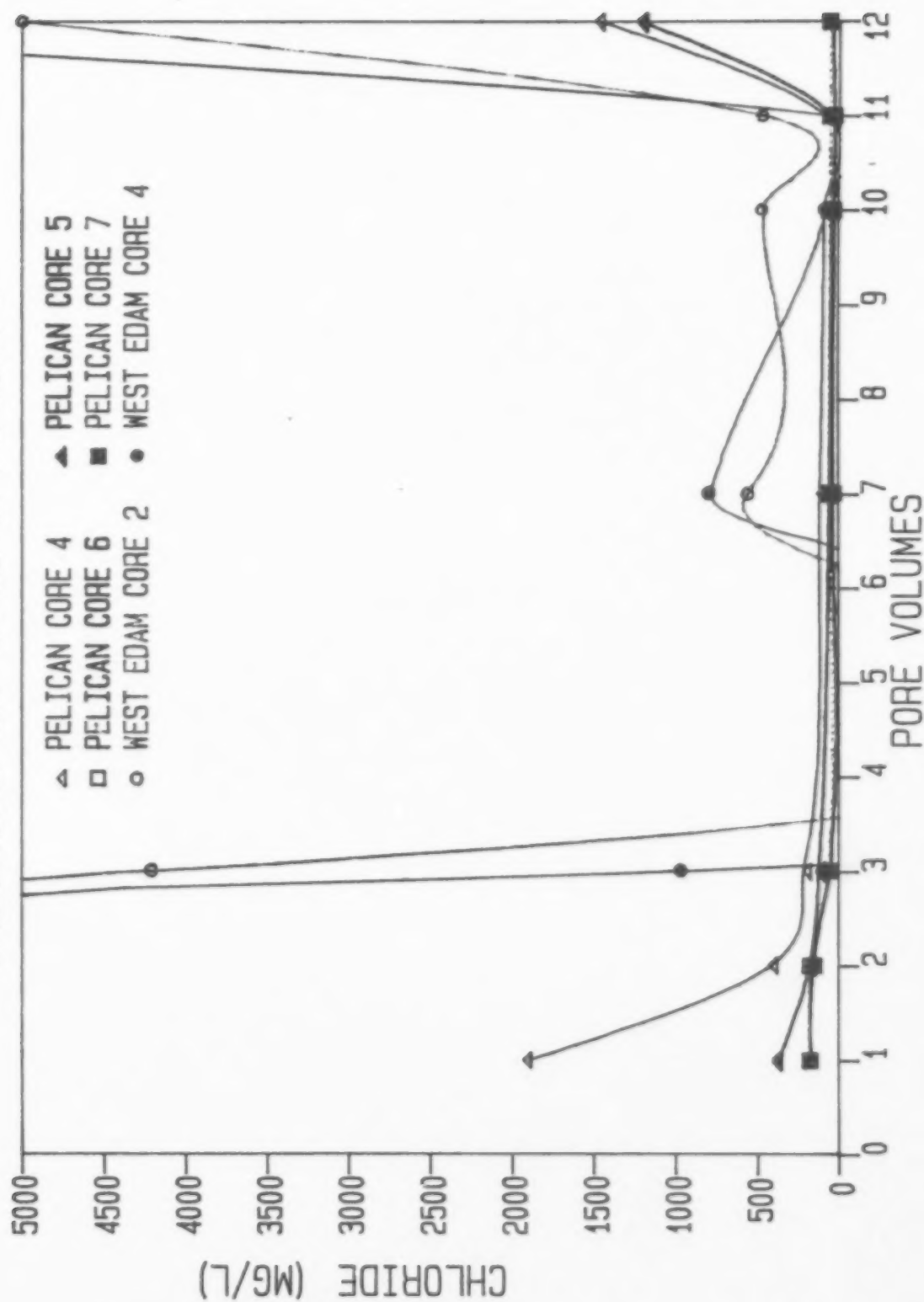


FIGURE 20

SODIUM IN CORE EFFLUENTS

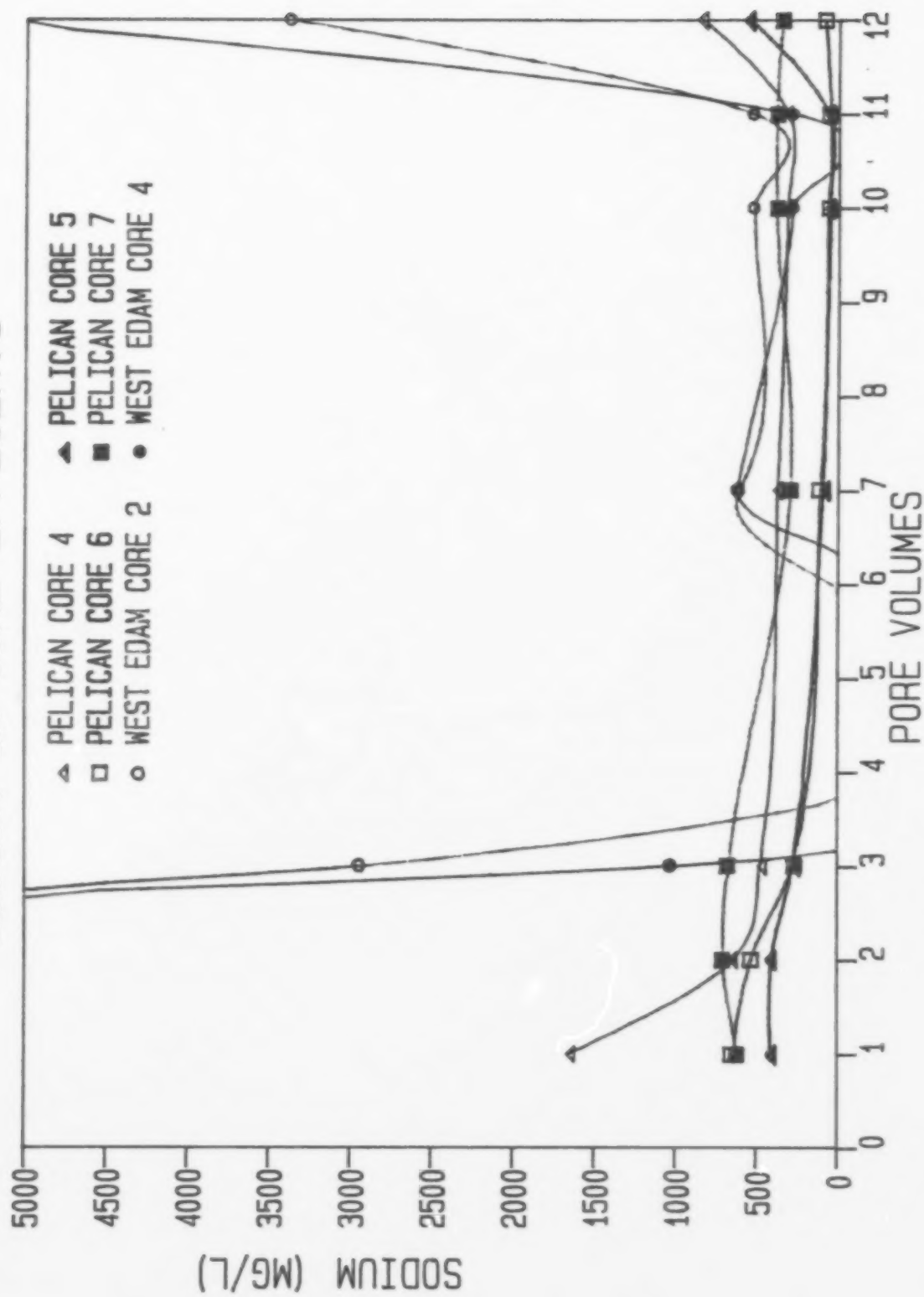


FIGURE 21

POTASSIUM IN CORE EFFLUENTS

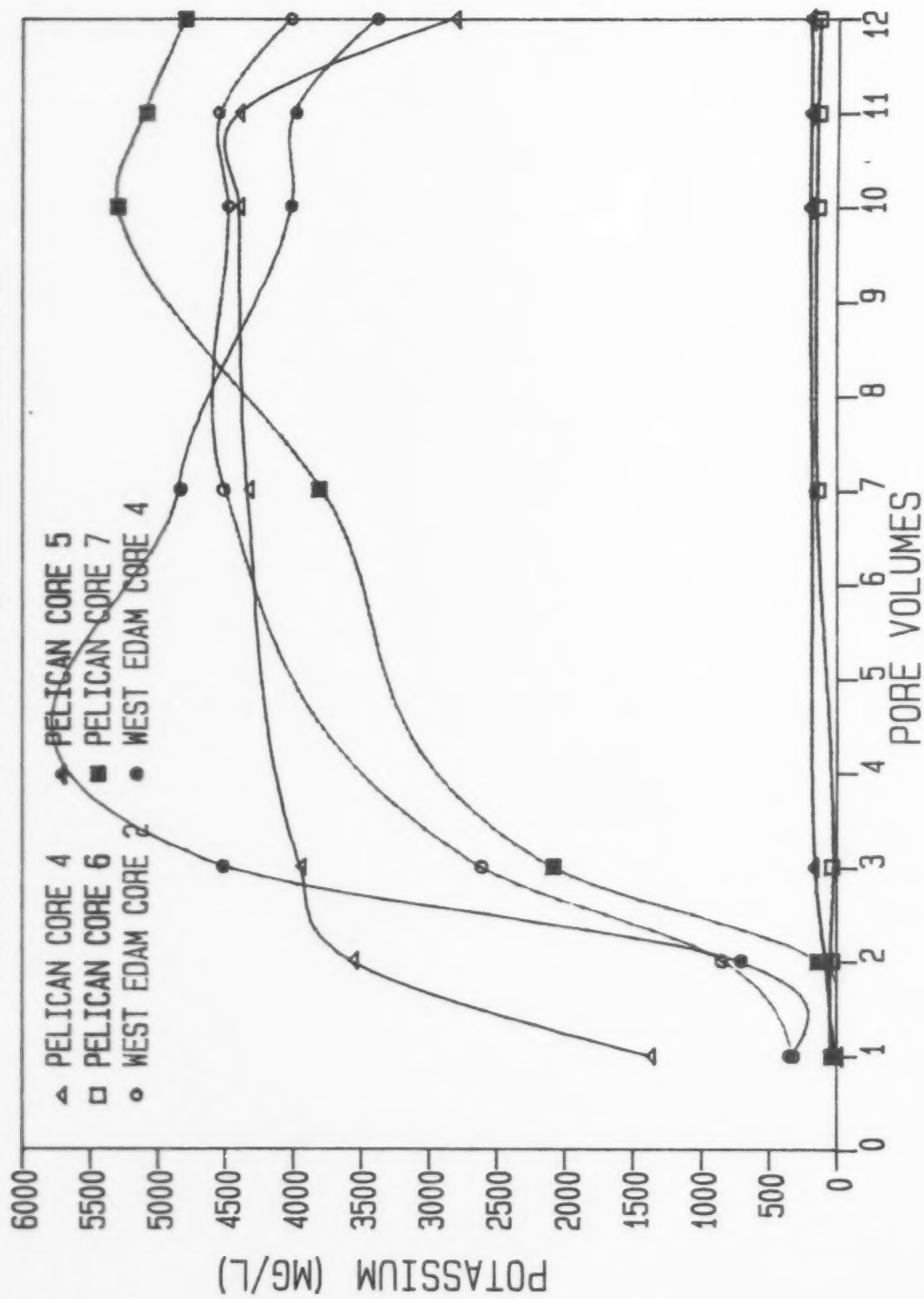


FIGURE 22

CALCIUM IN CORE EFFLUENTS

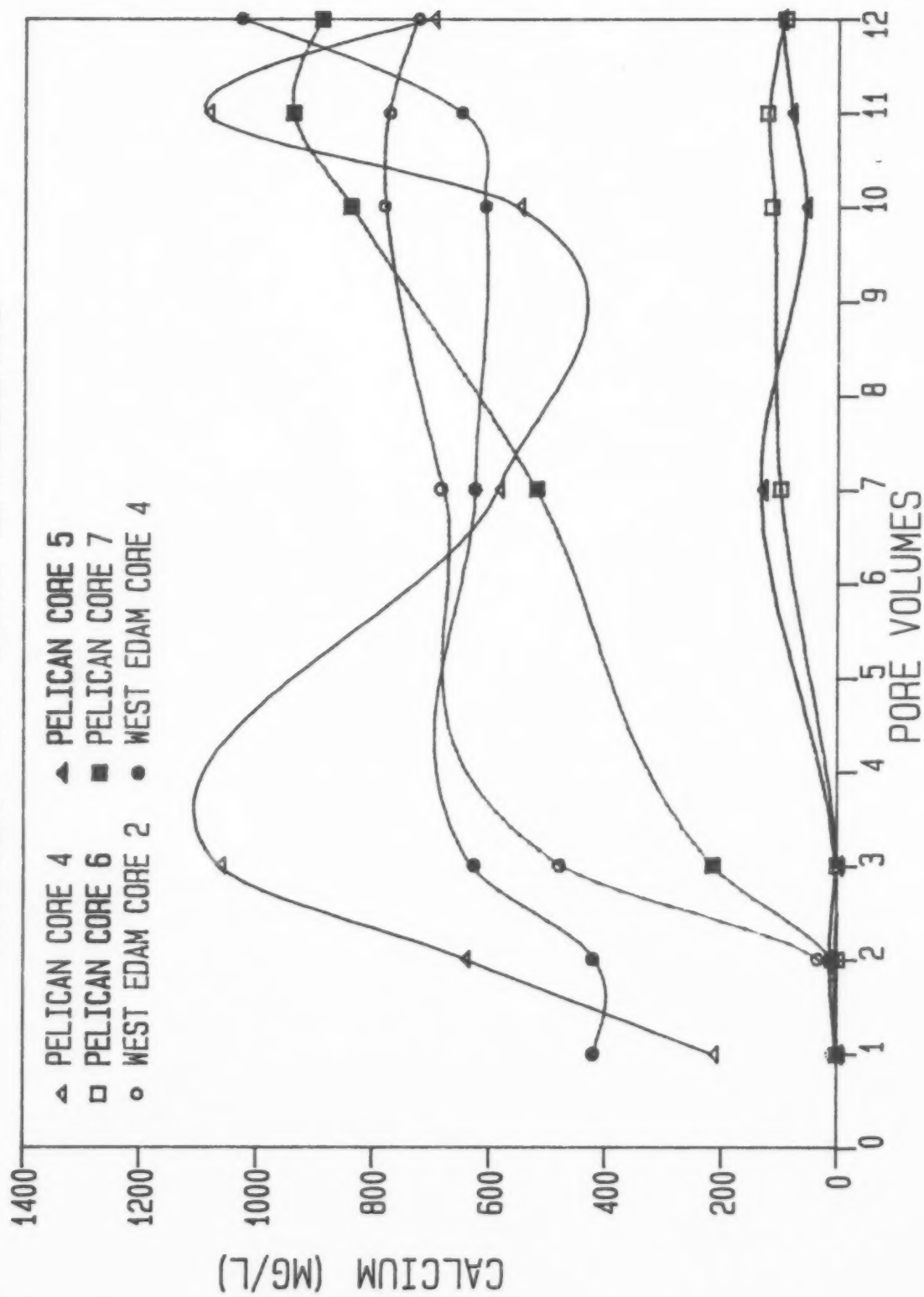


FIGURE 23

ALUMINUM IN CORE EFFLUENTS

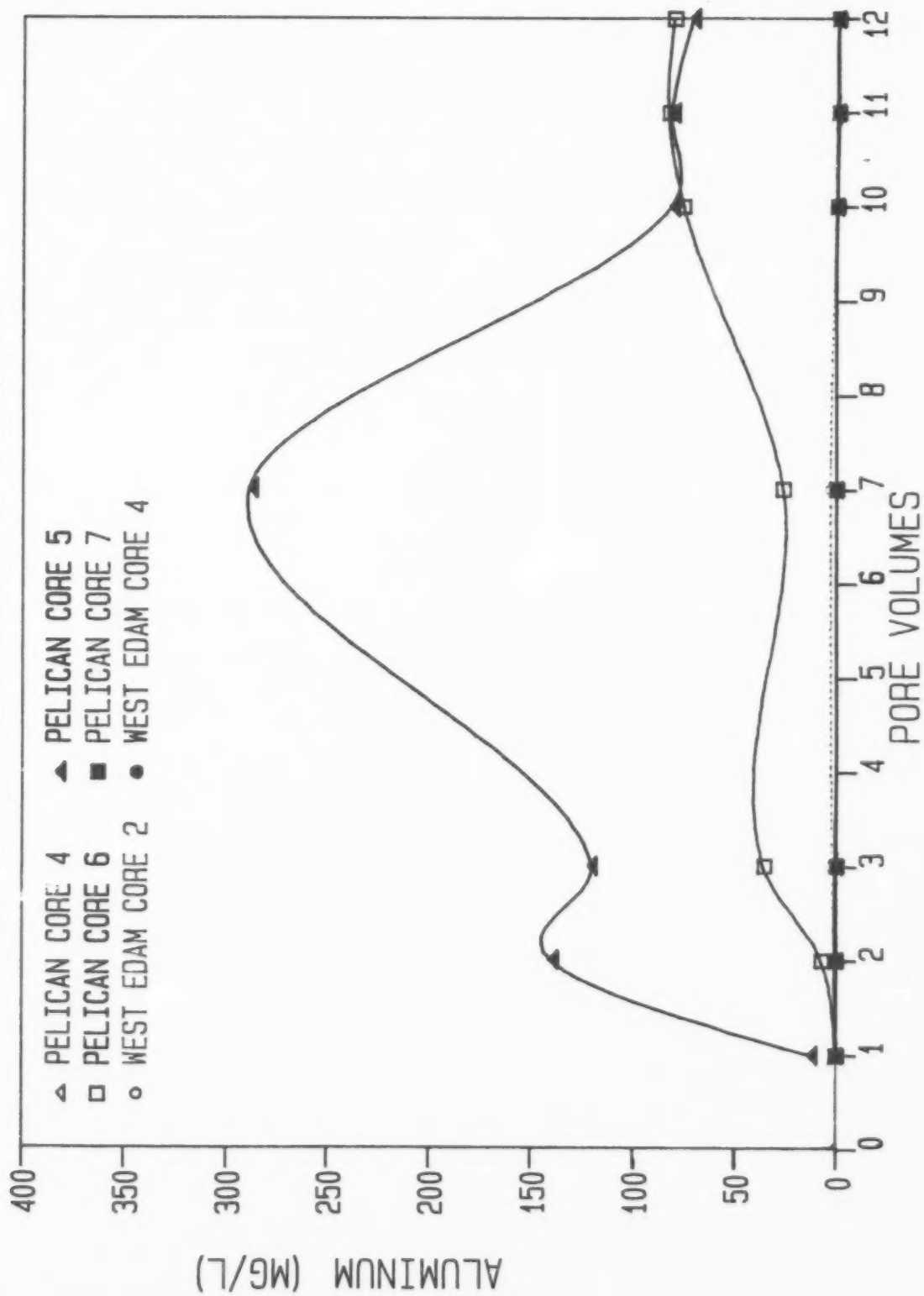


FIGURE 24

MAGNESIUM IN CORE EFFLUENTS

